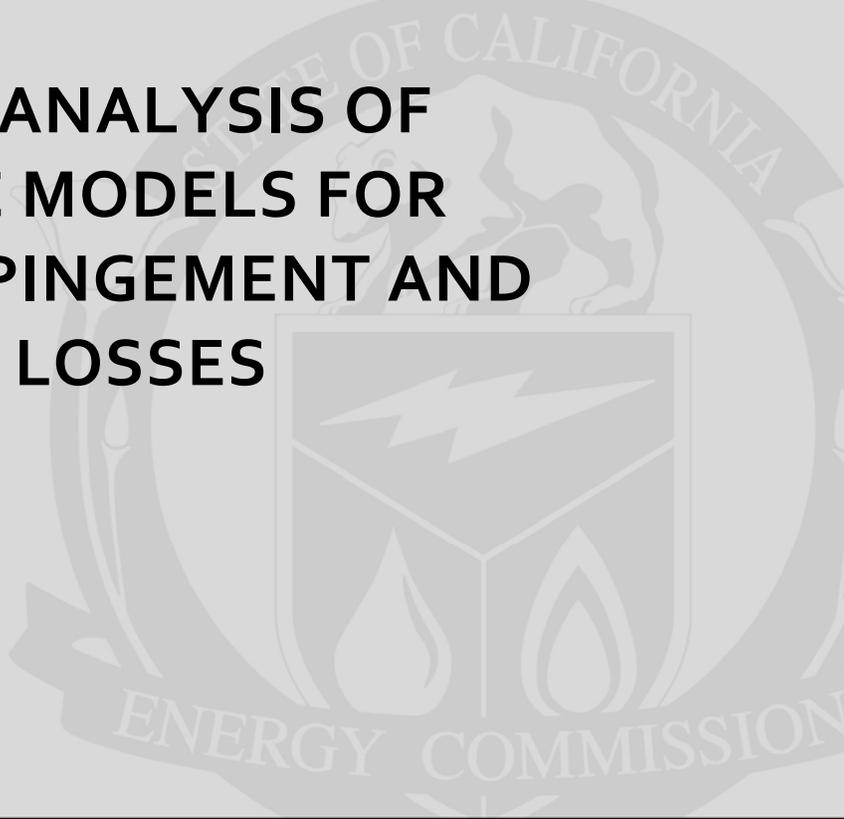


**Public Interest Energy Research (PIER) Program  
FINAL PROJECT REPORT**

**A SENSITIVITY ANALYSIS OF  
DEMOGRAPHIC MODELS FOR  
ASSESSING IMPINGEMENT AND  
ENTRAINMENT LOSSES**



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## PREFACE

The California Energy Commission Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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- Transportation

*A Sensitivity Analysis of Demographic Models for Assessing Impingement and Entrainment Losses* is the final report for the Once Through Cooling Research project (Contract Number 500-04-025) conducted by Stratus Consulting Inc. The information from this project contributes to PIER's Energy-Related Environmental Research Program.

For more information about the PIER Program, please visit the Energy Commission's website at [www.energy.ca.gov/research/](http://www.energy.ca.gov/research/) or contact the Energy Commission at 916-327-1551.

## ABSTRACT

This report discusses a sensitivity analysis of three demographic models used to evaluate impingement and entrainment losses of aquatic species resulting from the operation of cooling water intake structures at electric generating facilities that use once-through cooling. The models were the Adult Equivalent Loss model, the Fecundity Hindcasting model, and the Foregone Yield model. Uncertainty about the values of the life history parameters used to implement these models translates into uncertainty in model results. The authors performed a sensitivity analysis using Monte Carlo simulation to evaluate variation in model outputs with respect to uncertainty in parameter values. Distributions of values for model parameters were developed from data compiled through an extensive literature review. For each model, the sensitivity analysis estimated the net uncertainty associated with different applications of the model and ranked the relative contribution of each model parameter to total uncertainty. The relative precision of the models varied widely depending on whether they were applied to entrainment or impingement losses, and also among species. For entrainment-related impacts, the precision of the Fecundity Hindcasting model was greater than the other two models for six of seven species groups. For impingement-related impacts, the Adult Equivalent Loss model was more precise than the other two models. Parameter ranking indicated that uncertainty about larval mortality rates was generally the most important source of uncertainty for the Adult Equivalent Loss model, uncertainty about fishing mortality rates were most important for the Foregone Yield model, and uncertainty about lifetime fecundity was most important for the Fecundity Hindcasting model. The report discussed implications of the sensitivity analysis for interpreting results of the demographic models and for prioritizing future data collection to improve the reliability of model results.

### Keywords:

Impingement, Entrainment, Sensitivity analysis, Factor prioritization, Monte Carlo simulation, Demographic models, Fish modeling, Clean Water Act Section §316(b)

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# EXECUTIVE SUMMARY

## Introduction

A significant number of California's power plants sited along the state's coasts, bays, and estuaries use once-through cooling technology. This technology requires diverting large amounts of water from the ocean, bay, or estuary into the power plant's cooling system. These diverted water volumes can total from tens to hundreds of millions of gallons per day. In the power plant, the diverted water is passed once by the condenser to remove waste heat and then is discharged. Millions of small aquatic organisms, such as fish eggs and larvae that are carried along in this diverted water are often killed from thermal, physical, or chemical stresses as they pass through the power plant; this impact is referred to as *entrainment*. Other, larger organisms are trapped against screens on the cooling water intake or within the intake itself; this is known as *impingement*. Power plant operators are required to assess and, if appropriate, mitigate or compensate for the ecological losses from entrainment and impingement.

Since these ecological losses occur to a variety of species at different life stages, many at the larval or egg stage, demographic models are usually used to assess the importance of impingement- and entrainment-related losses. These models convert numbers of organisms killed at various ages, usually fish eggs and larvae, into standardized metrics. Three of the most commonly used demographic models are the Adult Equivalent Loss model, which converts losses of early life stages into equivalent numbers of adults of a given age; the Fecundity Hindcasting model, which estimates the total number of adult females required to produce the number of larvae lost to entrainment (i.e., equivalent spawners); and the Foregone Yield model, which estimates the yield (biomass) of fishery species that is not harvested because fish are killed by impingement and entrainment.

Demographic models require data on species- and age-specific fecundity (potential reproductive capacity) and mortality rates. However, for most fish and aquatic invertebrates, values for fecundity and mortality parameters have a high degree of uncertainty. The uncertainty in input data translates into uncertainty in model predictions, complicating the interpretation of model results. As a result, conclusions about the ecological significance of impingement and entrainment can vary depending on the input data used to generate model results. Although understanding the uncertainty in demographic models is therefore critical for evaluating impingement and entrainment losses, few quantitative analyses of uncertainty in this context have been conducted.

## Project Purpose

The overall goal of this study was to quantify how uncertainty about the values of the input parameters of the Adult Equivalent Loss model, Fecundity Hindcasting, and Foregone Yield models translates into uncertainty in calculated measures of impingement and entrainment losses, and to determine the relative contribution of individual parameters to total uncertainty. Results of these analyses will provide regulators with a better understanding of the uncertainties associated with reported impingement and entrainment loss rates. The results will also help to guide and prioritize future data collection efforts designed to improve the reliability

of impact assessments of facilities that must comply with Section §316(b) of the Clean Water Act, which requires that the location, design, construction and capacity of cooling water intake structures reflect the best technology available for minimizing adverse environmental impacts.

## Project Results

An extensive literature review assembled demographic parameters for seven species groups commonly impinged and entrained in California: anchovies (*Engraulidae*), gobies (*Gobiidae*), blennies (*Blenniidae* and *Chaenopsidae*), California halibut (*Paralichthys californicus*), rockfishes (*Sebastes* spp.), surfperches (*Embiotocidae*), and crabs of the genus *Cancer*. Based on this review, the authors identified a “best estimate” and reasonable ranges of values for each input parameter evaluated. This information was used to construct a distribution of values for each parameter.

Using Monte Carlo simulation, a method for statistical sampling from distributions of parameter values, a sensitivity analysis was conducted to estimate the uncertainty associated with different applications of each model. In each of thousands of simulations of a given model, values for certain input parameters were randomly sampled from the distribution of values and were used to calculate the value of the demographic metric. By conducting multiple simulations with systematic differences in which parameter values were variable or fixed as constants, the relative contribution of each parameter to total uncertainty was quantified and ranked, a procedure known as a “factor prioritization.” The results of the simulations were also quantified as a coefficient of variation (CV) that was used to describe the relative precision of results provided by the various demographic models. For this analysis, the CV was the standard deviation among outcomes for a particular simulation divided by the point estimate for a particular application.

The precision of the Fecundity Hindcasting model was greater than either the Adult Equivalent Loss or the Foregone Yield models for anchovies, gobies, California halibut, rockfishes, and crabs. For these species, the ordering of the three models from most to least precise was Fecundity Hindcasting > Adult Equivalent Loss > Foregone Yield. The coefficient of variation of the Fecundity Hindcasting model applied to entrainment ranged from 0.13 to 0.75 for these species. Blennies were an exception, with the Adult Equivalent Loss model being more precise than the Fecundity Hindcasting model. Uncertainty about lifetime fecundity was the largest contributor to uncertainty for anchovies and blennies. Uncertainty in mortality rates of early life stages were the largest contributors for gobies, rockfish, California halibut, and crabs.

Uncertainty in larval mortality rates was the largest source of uncertainty for anchovies, California halibut, and crabs in the results of the Adult Equivalent Loss model. Uncertainty about larval mortality rates was also the largest source of uncertainty in the Adult Equivalent Loss model applied to blennies and gobies except when uncertainty about entrainment rates exceeded +/-70 percent or +/-90 percent, respectively. For rockfishes, mortality of young-of-the-year (age zero+) fish was the greatest contributor to uncertainty using the Adult Equivalent Loss model.

Uncertainty in the Foregone Yield model was not associated with a single parameter. Uncertainty in entrainment loss and mortality rates of all age classes vulnerable to fishing mortality contributed to total uncertainty to a similar degree.

For impingement losses, the precision of the Adult Equivalent Loss model was greater than the other models for all species groups. The ordering of the three models from most precise to least precise was Adult Equivalent Loss > Foregone Yield > Fecundity Hindcasting. The correlation of variation of the Adult Equivalent Loss model applied to impingement losses ranged from 0.04 to 0.22.

When either the Adult Equivalent Loss model or the Foregone Yield model was applied to impingement losses, the relative contributions of the parameters to total uncertainty depended on what was assumed regarding the amount of uncertainty in the impingement rate. With the Adult Equivalent Loss model, uncertainty about impingement rate predominated if the assumed uncertainty in impingement rates exceeded about 5 percent for anchovies or gobies, about 15 percent for blennies or California halibut, about 35 percent for surfperches, and about 55 percent for rockfishes. For crabs, uncertainty in estimated impingement was a greater contributor to total uncertainty than mortality rates at any age. With the Foregone Yield model, uncertainty in mortality rates of age classes vulnerable to fishing mortality were the greatest contributors to total uncertainty, but for some species uncertainty in impingement rates was predominant if uncertainty about impingement exceeded 10-25 percent.

For anchovies, California halibut, and crabs, uncertainty about larval mortality rates was the most important contributor to uncertainty using the Fecundity Hindcasting model. For rockfishes, uncertainty about age zero+ mortality rates was the most important contributor to uncertainty. For blennies and surfperches, uncertainty about lifetime fecundity was the most important contributor to uncertainty.

Because of the different ages of impinged and entrained species, a model that provides the most precise estimate for evaluating impingement may not provide the most precise estimate for evaluating entrainment. For assessing entrainment, the Fecundity Hindcasting model was more precise than either the Adult Equivalent Loss model or the Foregone Yield model for most species. For assessing impingement, the precision of the Adult Equivalent Loss model was greater than the other models for all species evaluated.

For a given facility, uncertainty in results of the Adult Equivalent Loss model applied to entrainment could be made more precise by collecting locally-specific larval mortality rates, assuming that such studies provide mortality estimates that have less uncertainty than the estimates from the literature review. This is consistent with the fact that larvae dominate entrainment losses. However, the available literature indicated substantial uncertainty regarding larval survival for most species, suggesting that it could prove difficult to improve larval survival estimates, even with local studies. Uncertainty in results of the Foregone Yield model applied to entrainment could be made more precise by acquiring more precise estimates of mortality rates among older age classes, particularly age classes vulnerable to fishing mortality.

Alternatively, the study results suggested that the Fecundity Hindcasting model may be the most reliable way to assess entrainment losses, particularly if more precise estimates of lifetime fecundity were identified. It is likely that improving estimates of lifetime fecundity will not only be more tractable but also less costly than obtaining more precise estimates of larval mortality rates.

The authors recommended that §316(b) studies quantify the precision of annual impingement, entrainment, fecundity, and mortality rates to help analysts interpret metrics derived with the three models used in this analysis. Specific recommendations include:

- Using the Fecundity Hindcasting model for assessing entrainment losses because estimation of equivalent spawners can be done with greater precision than estimation of age one equivalents or foregone yield.
- Improving the utility of the Fecundity Hindcasting model applied to entrainment by focusing additional field research on improving estimates of lifetime fecundity.
- Using the Adult Equivalent Loss model for assessing impingement losses, because for older individuals, estimation of age one equivalents can be done with greater precision than estimation of foregone yield or equivalent spawners.
- Improving the utility of the Adult Equivalent Loss model applied to entrainment or impingement by focusing additional field research on early life stage survival rates.
- Using caution when applying any of the models to crabs because uncertainties about mortality rates for this group are relatively large, particularly in comparison to fish species. Because entrainment losses of crab larvae can be very large, additional research should focus on crab species if uncertainty is to be reduced meaningfully.
- Improvement in model uncertainty will also depend on reducing the uncertainty in impingement and entrainment loss estimates. Therefore, researchers should strive to ensure that these estimates are as precise as possible (preferably +/-10 percent or less).
- In §316(b) studies, quantify the precision of annual impingement, entrainment, fecundity, and mortality rates to help analysts interpret metrics derived with the Adult Equivalent Loss, Foregone Yield, and Fecundity Hindcasting models.
- Consider developing performance standards for the acceptable degree of uncertainty in §316(b) studies that rely on any of the alternative metrics of entrainment or impingement losses, including uncertainty about actual loss rates and uncertainty in estimates derived from demographic models.

## Project Benefits

The results of this study can be used by regulators who must interpret reported impingement and entrainment loss rates and assess their ecological significance. Use of demographic models makes it possible to express losses of organisms in multiple age classes in standardized terms that help to put losses of eggs and larvae in context. However, there can be significant

uncertainties in results of these models depending on uncertainties in model inputs. The results of the study may also help regulators define acceptable levels of uncertainty in future entrainment and impingement studies. Finally, the results of the sensitivity analysis and factor prioritization presented in this study can help prioritize future data collection to reduce uncertainty about parameter values that have the greatest influence on uncertainty in the results of the demographic models evaluated.



# CHAPTER 1: Introduction

## 1.1 Background

In California, twenty-one coastal power plants use once-through cooling for electric energy production. When cooling water intake structures withdraw water from ocean and estuarine waters, organisms in the water column are trapped against intake screens (impingement) or drawn into the power plant's cooling system (entrainment), resulting in the mortality of billions of eggs, larvae, and juveniles of estuarine and marine fishes and macroinvertebrates such as crabs (EPRI 2007; York and Foster 2005).

The U.S. Environmental Protection Agency (EPA) is developing regulations to minimize the adverse impacts of cooling water intake structures, pursuant to section 316(b) of the federal Clean Water Act (CWA) (33 U.S.C. §1326). Section 316(b) provides that

Any standard established pursuant to section 1311 [CWA §301] or section 1316 [CWA §306] and applicable to a point source shall require that the location, design, construction, and capacity of cooling water intake structures reflect the best technology available for minimizing adverse environmental impact.

EPA has interpreted Section 316(b) to mean that “adverse aquatic environmental impacts occur whenever there will be entrainment or impingement damage as a result of the operation of a specific cooling water intake structure” (U.S. EPA 1977).

The State of California Water Quality Control Board and associated regional boards implement section 316(b) under the federal National Pollutant Discharge Elimination System program. The California Energy Commission has authority for certifying any new or expanded facility with greater than 50-megawatt (MW) capacity, pursuant to the 1974 Warren-Alquist Act (Public Resources Code Section 25000 et seq.). The California Coastal Commission also has an important role in the review of re-powering projects in the coastal zone.

Aquatic organisms, particularly planktonic early life stages, can be difficult to sample. As a result, often there is a lack of relevant data on life history characteristics such as fecundity and mortality rates for most species that are impinged and entrained. These data are necessary to express losses of eggs, larvae, and juveniles in terms of common demographic metrics. Such data are also necessary to quantify restoration actions (Strange et al. 2004, 2008).

Demographic models can be used to translate impingement and entrainment losses into common metrics. However, the uncertainty in these models has received little attention. This report presents results of an analysis to quantify uncertainties in the assessment of impingement and entrainment losses, identifies preferable strategies for application of the models, and identifies priorities for future data collections that may improve their precision.

## 1.2 Project Objectives

The overall goal of this project was to conduct a sensitivity analysis to examine variation in the outputs of three demographic models used to assess impingement and entrainment. A sensitivity analysis is a way to systematically investigate how models are affected by uncertainty and variability in model inputs (Cariboni et al. 2007, Saltelli 2005, Saltelli et al. 1999, Finkel 1990; Morgan and Henrion 1990). Knowledge of parameters that are most influential in demographic models of impingement and entrainment will help to efficiently manage decisions about which life history parameters are important to characterize more accurately and will help to prioritize future studies.

We conducted a sensitivity analysis to evaluate uncertainty in values of model input parameters and the metrics calculated by three demographic models that are commonly used to evaluate impingement and entrainment losses. Although conceptually sound, the models are dependent on a large number of age-specific life history parameters, including age-specific growth, mortality, and fecundity. The values of these parameters are poorly known for many animal populations, particularly for early life stage (ELS) fishes and invertebrates in oceans and estuaries that can be difficult and costly to sample.

The sensitivity analysis was designed to estimate the uncertainty associated with different applications of each of the three demographic models and to rank the relative contribution of model parameters to each model's total uncertainty. The goals of the analysis were to:

- For six species groups using three demographic models, identify the total uncertainty in model outputs, representing the combined effects of uncertainty in multiple species-specific vital rates and uncertainty in numbers of organisms killed by impingement and entrainment.
- Identify the relative precision of the three models for each species group.
- Identify the life history parameters that have the greatest influence on results of the demographic models.
- Quantify the relative precision of model estimates using various assumptions about model parameter values.
- Determine high priority data needs for reducing uncertainty in the results of the demographic models.

# CHAPTER 2: Project Approach

## 2.1 Demographic Models Evaluated

The three demographic models we evaluated with the sensitivity analysis were the Adult Equivalent Loss (AEL) model, the Forgone Yield (FY) model, and the Fecundity Hindcasting (FH) model. Each of the models uses species-specific demographic rates (mortality, fecundity, and growth) to express impingement and entrainment losses in terms of a common standardized metric. The standardized metrics derived using each of the three models represent distinct demographic concepts. The AEL model converts losses of early life stages into equivalent numbers of adults of a given age. In our analysis we expressed losses as age 1 equivalents. The FY model is used to estimate the yield (biomass) of fish or shellfish that cannot be harvested because they are killed by impingement and entrainment. The FH model estimates the total number of adult females required to produce the number of larvae lost to entrainment (i.e., equivalent spawners). The methods used to calculate these metrics are described in more detail in the following sections.

### 2.1.1 Adult Equivalent loss Model

The AEL model is a method for expressing impingement and entrainment losses as an equivalent number of individuals at some other life stage, referred to as the age of equivalency (Horst 1975; Goodyear 1978). The method provides a convenient means of converting numbers of organisms killed at various ages into “equivalent” numbers or organisms of a single specified age and thereby provides a standard metric for comparing losses among species, years, and regions.

For any given species, the AEL calculation requires stage-specific impingement and entrainment loss and mortality rates to determine a ratio to convert numbers of organisms killed to the equivalent numbers at a selected age (age 1 in our analyses). For impinged fish that are older than age 1, age 1 equivalents are calculated by modifying the basic calculation to increase the loss rates in inverse proportion to survival rates. The basic procedure is defined as:

$$S_{j,1} = S_j^* \prod_{i=j+1}^{j_{\max}} S_i \quad (\text{Equation 1})$$

Where:

$S_{j,1}$	=	cumulative survival from stage $j$ until age 1
$S_j^*$	=	$2S_j e^{-\log(1+S_j)}$ = adjusted $S_j$
$j_{\max}$	=	the stage immediately prior to age 1
$S_i$	=	survival fraction from stage $i$ to stage $i + 1$ .

Equation 1 defines  $S_{j,1}$ , which is the expected cumulative survival rate (as a fraction) from the stage at which entrainment occurs,  $j$ , through age 1. The components of Equation 1 represent survival rates during the different life stages between life stage  $j$ , when a fish is entrained, and

age 1. Survival through the stage at which entrainment occurs,  $j$ , is treated as a special case because the amount of time spent in that stage before entrainment is unknown and therefore the known stage specific survival rate,  $S_j$ , does not apply because  $S_j$  describes the survival rate through the entire length of time that a fish is in stage  $j$ . Therefore, to find the expected survival rate from the day that a fish was entrained until the time that it would have passed into the subsequent stage, an adjustment to  $S_j$  is required. The adjusted rate  $S^*_j$  describes the effective survival rate for the group of fish entrained at stage  $j$ , considering the fact that the individual fish were entrained at various specific ages within stage  $j$ . Age 1 equivalents are then calculated as:

$$AE1_j = L_j S^*_{j,1} \quad (\text{Equation 2})$$

Where:

$L_j$  = the number of killed organisms of age  $j$ .

The total number of age 1 equivalents derived from losses at all stages is then given by:

$$AE1 = \sum_{j=j_{\min}}^{j_{\max}} AE1_j \quad (\text{Equation 3})$$

Where:

$AE1$  = the total number of age 1 equivalents derived from losses at all stages.

In summary, adult equivalency metrics express observed impingement and entrainment losses in terms of the equivalent number of organisms at a specific selected age. The fundamental feature of adult equivalency modeling is the definition of a set of ratios that describe the proportion of organisms killed by impingement and entrainment to the numbers of those organisms that would have lived to a particular age if they had not been killed. The ratios are determined by the age-specific cumulative survival rates between the age of the entrained or impinged organism and the selected age of equivalency. Typically relevant survival rates are not known with a high degree of certainty. Uncertainty about the survival rates translates into uncertainty about the relevant conversion ratios and hence uncertainty about the value of the standardized metric.

### 2.1.2 Forgone Fishery Yield

Forgone fishery yield (FY) is a measure of the amount of fish or shellfish (as biomass) that cannot be harvested because of impingement and entrainment mortalities. We estimated forgone yield using the Thompson-Bell equilibrium yield per recruit model (Ricker 1975). The model provides a simple method for evaluating a cohort of fish that enters a fishery in terms of their fate as harvested or not-harvested individuals. Our application of the Thompson-Bell model assumes that impingement and entrainment losses result in a reduction in the number of harvestable adults in years after the time that individual fish are killed by impingement and entrainment (U.S. EPA 2004).

The Thompson-Bell model is based on the same general principles that are used to estimate the expected yield in any harvested fish population (Hilborn and Walters 1992; Quinn and Deriso 1999). The general procedure involves multiplying age-specific harvest rates by age-specific weights to calculate an age-specific expected yield (as biomass). The lifetime expected yield for a cohort of fish is then the sum of all age-specific expected yields, thus:

$$Y = \sum_j \sum_a L_j S_{ja} W_a (F_a / Z_a) \quad (\text{Equation 4})$$

Where:

$Y$	=	forgone yield (biomass) due to impingement and entrainment losses
$L_j$	=	losses of individual fish of stage $j$
$S_{ja}$	=	cumulative survival fraction from stage $j$ to age $a$
$W_a$	=	average weight of fish at age $a$
$F_a$	=	instantaneous annual fishing mortality rate for fish of age $a$
$Z_a$	=	instantaneous annual total mortality rate for fish of age $a$ .

The model assumes that:

- The yield from a cohort of fish is proportional to the number recruited
- Annual growth, natural mortality, and fishing mortality rates are constants
- Natural mortality includes mortality from impingement and entrainment.

In summary, forgone yield models are generally similar to the AEL model but they extend the reasoning of AEL model to include a multiple ages and to consider the proportion of the organisms that would have been harvested, had they not been killed by impingement and entrainment. As with the AEL model, the parameters of forgone yield models include age-specific survival rates, as well as age-specific fishing mortality rates and weights. The basic result of forgone yield models is a ratio that describes the incremental loss of harvested fish, as biomass. This type of ratio is commonly known as a “yield per recruit” ratio (YPR). In the context of impingement and entrainment modeling a set of YPR values are required with distinct values corresponding to each of the age classes that are subject to impingement and entrainment mortality. Here the concept of a “recruit” is not fixed at a particular age, but instead the effective meaning is yield per organism killed by impingement and entrainment and a particular age. Uncertainties about natural mortality rates and fishing mortality rates translate into uncertainty about YPR ratios.

### 2.1.3 Fecundity Hindcasting

FH is a method used to estimate the number of adult females required to produce the number of organisms lost to impingement and entrainment. The number of age-specific losses is projected backward to estimate an equivalent number of eggs, and then an estimate of lifetime fecundity is used to convert numbers of eggs into the corresponding number of female adults

(“equivalent spawners”). Results give an indication of the number of adult females effectively removed from the reproductive population as a result of entrainment. The equation used to calculate FH is:

$$FH = (1/F) \sum_j E_j / \prod S_{ej} \quad (\text{Equation 5})$$

Where:

- $E_j$  = annual entrainment of organisms of age  $j$
- $S_{ej}$  = cumulative survival rate from egg stage to stage  $j$
- $F$  = expected number of eggs produced in a reproductive lifetime.

FH models express impingement and entrainment losses in terms of the number of female spawning fish that could produce the number of organisms killed by impingement and entrainment (equivalent spawners). Ratios that relate the number of organisms killed by impingement and entrainment are determined by the cumulative mortality rate between the egg stage and the age at which impingement and entrainment mortality occurs and the expected lifetime fecundity of the species. Uncertainties about age specific fecundity (eggs/female) and age specific survival rates translate into uncertainty about expected lifetime fecundity. Uncertainty about survival rates and expected lifetime fecundity translate into uncertainty about estimates of equivalent spawners.

## 2.2 Life History Parameters Evaluated

The life history parameters that were evaluated in the sensitivity analysis included fishing mortality, natural (nonfishing) mortality, and fecundity. Mortality rates were stage-specific whereas fecundity was represented as total lifetime fecundity. A constant set of weight-at-age values was used in the FY model. None of the models evaluated included dynamic terms to account for density dependence.

In this report we use the terms “stage” and “age” interchangeably. For fish age one and older, a stage corresponds directly to the age in years of the fish. For fish younger than age one, loss data for early life stages were assigned to one of three life stages (eggs, larvae, and age 0+). Age 0+ refers to a post-larval individual that has not yet lived a full year. If the literature provided mortality rates for a more detailed staging scheme (e.g., yolk-sac larvae or post-yolk-sac larvae), the rates were combined to reflect mortality for the entire larval life stage. In cases where the literature reported daily instantaneous rates, the reported values were multiplied by the stage duration (days) to determine mortality rate for the entire stage. The mortality rates (and their ranges) used in the analysis are all expressed as instantaneous rates for the entire duration of the stage. Expressing a mortality as an instantaneous rate means the decrease in numbers of individuals in a population over time are modeled as an exponential decay process and the mortality rate parameter ( $Z$ ,  $M$ , or  $F$ ) relates to survival rate (as a fraction of a population) according to Equation 7. Larger values of  $Z$ ,  $M$ , or  $F$  imply smaller survival rates.

Published fishing mortality rates ( $F$ ) were assumed to reflect combined mortality due to both commercial and recreational fishing. Basic fishery science relationships (Ricker 1975) among mortality and survival rates were assumed:

$$Z = M + F \quad \text{(Equation 6)}$$

Where:

$Z$  = the total instantaneous mortality rate  
 $M$  = natural (nonfishing) instantaneous mortality rate  
 $F$  = fishing instantaneous mortality rate

and:

$$S = e^{(-Z)} \quad \text{(Equation 7)}$$

Where:

$S$  = the survival rate as a fraction.

Depending on which mortality rates were reported in the various data sources, the parameters  $Z$ ,  $M$ , or  $F$  were deduced according to Equation 6 and Equation 7. In the Monte Carlo simulations,  $Z$  and  $F$  were subject to randomized variability and  $M$  was found by subtraction ( $M = Z - F$ ).

Fecundity refers to the reproductive capacity of an individual, usually measured as the number of eggs produced by a female in a specific period of time (Murphy and Willis 1996). In viviparous species, fecundity refers to the number of young fish that are released after gestation. Our analyses required values of lifetime fecundity, however literature often provided fecundity rates related to organisms of particular ages or weights. In such cases we took steps to convert such values into estimates of lifetime fecundity. Similarly, if the literature provided the number of eggs or offspring produced in a single spawning event and the number of spawning events per year, we estimated annual fecundity as the sum of each spawning event over a year. In order to utilize reports that expressed fecundity as a function of size or age, we used published relationships among age, length, and weight. When age was not reported but length was, we used a von Bertalanffy equation (Phillips 1964) to solve for age given length:

$$A_t = L_0 - (1/k)[\log_e(1 - (L_t/L_\infty))] \quad \text{(Equation 8)}$$

Where:

$A_t$  = age at time  $t$  (years)  
 $L_0$  = length at age zero.  
 $L_\infty$  = maximum length  
 $L_t$  = length at time  $t$   
 $k$  = growth rate constant.

Application of the Bertalanffy equation requires information on species growth rates or length and age estimates. Information on age/weight, age/length, and weight/length relationships was also useful in determining age or stage durations for given life history parameters when not provided. These relationships were characterized on a species specific basis. The expected value of lifetime fecundity per female was estimated by reference to age-specific fecundity and total mortality rates ( $Z$ ).

## 2.3 Sensitivity Analysis

### 2.3.1 Monte Carlo Modeling

We conducted the sensitivity analysis using Monte Carlo modeling, a method used to quantify overall uncertainty in model results based on the amount of uncertainty in each of the various input parameters (Cariboni et al. 2007, Saltelli 2005, Saltelli et al. 1999, U.S. EPA 1997). It is a computational approach to assessing variation in a statistic (e.g., the outputs of the demographic models) by recalculating the statistic a large number of times using different parameter values for each calculation drawn from a statistical distribution of the parameter values. The variation in parameters values used in each successive calculation is selected to reflect the amount of uncertainty associated with the original estimates of the parameter values.

For each of the assessment models analyzed (AEL, FY, FH), we conducted a sequence of distinct Monte Carlo calculations with a systematic design of fixed and varying model parameters. For each model, the variable parameters included population mortality rates and the number of organisms killed annually by impingement or entrainment (“loss rates”). Natural and fishing mortality rates were considered jointly for each life stage, i.e., both variables were held constant when the objective was to fix mortality rates at constant levels. In the FH model lifetime fecundity was also varied (fecundity is not a parameter in the FY or AEL model).

### 2.3.2 Statistical Distributions Used in Monte Carlo Simulations

A crucial aspect of a Monte Carlo simulation approach to sensitivity analysis is a statistical description of the uncertainty about each of the parameters (Lipton et al. 1995). These descriptions are important because they define the sampling distribution of values selected at random during each iteration of the Monte Carlo simulation. The sampling distributions used should reflect biologically-realistic values and should also reflect the distribution of uncertainty with a level of detail commensurate with the available information.

We evaluated the data we gathered from an extensive literature review to identify the central tendency among the values of each model input parameter, as well as a range of plausible values for each of these parameters. The literature includes many reports that collectively provide information about the uncertainty of the parameter values, but individual reports that address the question of uncertainty are relatively rare, therefore we integrated information from multiple data sources. The process was not strictly empirical and involved our best professional judgment. The integration process led to estimates of a most likely value of each parameter as well as upper and lower limits on plausible values. The minimum, modal (most likely), and maximum values identified in this manner were interpreted as three parameters of a triangular distribution that was the basis of the Monte Carlo sampling.

A triangular distribution was chosen to represent the uncertainty in parameter values because it reflects our interpretation of the level of detail provided by our literature sources. The available literature allowed us to identify minimum, maximum and modal values, which made it possible to use a more detailed sampling distribution than a uniform distribution. However, the information did not support a more specific distributional form such as a normal distribution.

We also modeled ranges of uncertainty associated with estimates of impingement and entrainment rate using triangular distributions. For this purpose, point estimates of annual total impingement and entrainment loss rates in California were used as modal values and the lower and upper limits were defined as the point estimate plus or minus a selected percentage of the point estimate. For the primary analyses, the lower and upper limits on the loss rates were set to the point estimate +/-10 percent of the point estimate.

### 2.3.3 Factor Prioritization and Estimates of Precision

The sensitivity analysis was designed to provide a “factor prioritization,” a procedure for ranking the parameters in a model with respect to their relative contribution to the model’s total uncertainty. We conducted a factor prioritization for each species group and model, considering impingement and entrainment separately.

The methods we used for factor prioritization followed the methods attributed to Sobol (1993) and described by Cariboni et al. (2007), Saltelli (2005), Saltelli et al. (1999), and Chan et al. (1997). The parameter contributing most to the total uncertainty in a model output value is the parameter that, if uncertainty about that value were reduced to zero, would lead to the greatest reduction in uncertainty about the output value. Our approach to prioritizing (ranking) the parameters according to their contribution to variance in the model outputs is based on the definition of the “main effects” (or “first-order effects”) given by Sobol’ (1993). The statistics  $V_i$  represent the relative contribution of a particular factor to total uncertainty.  $V_i$  are determined by comparison of the variance in output values of the Monte Carlo simulations when all parameters values are variables versus variance in output values of the Monte Carlo simulations when the value of selected parameter ( $i$ ) is fixed at a constant value while all other parameters values are variables. Parameters associated with larger values of  $V_i$  are those that contribute relatively more to total uncertainty.  $V_i$  were estimated using the software algorithms of the R Sensitivity package (Pujols 2008).

As a complementary method of representing the contribution of each parameter to uncertainty in model outcomes, we defined the coefficient of variation (CV) as the ratio of the standard deviation among outcomes for a particular simulation divided by the point estimate for a particular application. Note that the point estimate of a particular application is determined by applying the model with all parameters fixed at their most probable (modal) values, while the standard deviation is determined from a distinct simulation where all but one of the parameter values were variables. The reported CVs therefore represent the amount of uncertainty in the model outputs values scaled to the magnitude of the point estimates. Larger values of CV indicate model conditions associated with a larger degree of uncertainty in the modeled value.

## 2.4 Impingement and Entrainment Data

To identify frequently impinged and entrained species, we analyzed loss data collected between 1978 and 2006 from 19 California facilities (Table 1). After assessing the magnitude and the frequency of impingement and entrainment at these facilities, we selected a set of species that had high rates of impingement and entrainment at multiple facilities, or were close surrogates of those species. These included anchovies (primarily northern anchovy, *Engraulis mordax*),

gobies (Gobiidae), blennies (Blenniidae and Chaenopsidae), *Cancer* crabs, California halibut (*Paralichthys californicus*), rockfishes (*Sebastes* spp.), and surfperches (Embiotocidae). Estimates of statewide annual loss rates (Table 2)<sup>1</sup> for the selected species groups were treated as uncertain values in the sensitivity analysis by expressing each of them as the modal value in a triangular distribution with minimum and maximum values assumed to be +/-10 percent in the primary factor prioritization. In secondary analyses designed to consider the importance of the assumed degree of uncertainty in the loss statistics, the ranges were set at +/-5 percent to +/-90 percent of the modal value. Secondary analyses were conducted with 3,000 replicates.

**Table 1: Summary of data sources used to estimate statewide annual impingement and entrainment loss rates in California**

Ecological zone	Facilities reporting impingement and entrainment losses	Impingement records considered	Entrainment records considered
	Facility name	(reporting years)	(reporting years)
Northern estuary	Hunters Point	1978	1978
Northern estuary	Potrero	1978	1978, 2001
Northern estuary	Contra Costa	1978, 1987-1990	1978, 1986-1992
Northern estuary	Pittsburg	1978, 1987-1990	1978, 1986-1992
Northern marine	Humboldt Bay	1980	1980
Midcoast estuary	Morro Bay	2000	2000
Midcoast estuary	Moss Landing	1979	1999
Midcoast marine	Diablo Canyon	1985	1997-1998
Southern marine	San Onofre	1990-2001	1979
Southern estuary	Alamitos	–	2006
Southern estuary	Encina	1979	–
Southern estuary	Haynes	2001	1979, 2006
Southern bay	Harbor	1979	1979, 2006
Southern coastal	Huntington Beach	1979-2001	–
Southern coastal	Redondo Beach	1991-2001	1979, 2006
Southern coastal	El Segundo	1990-2001	2006
Southern coastal	Scattergood	1990-2002	2006
Southern coastal	Ormond Beach	1990-2001	1979
Southern coastal	Mandalay	2001	–

<sup>1</sup>. The statewide rates developed for this study are intended to indicate the general magnitude of impingement and entrainment losses and the typical age distribution of individuals comprising the losses, and are not intended to be definitive indications of past, present, or future impingement and entrainment loss rates or for any purpose other than within the context of this study.

**Table 2: Estimates of annual impingement and entrainment losses of selected species groups used in sensitivity analysis of alternative assessment metrics**

Species	Age class	Annual entrainment		Annual impingement	
		Empirical <sup>a</sup>	Adjusted for assumed age distribution <sup>b</sup>	Empirical <sup>c</sup>	Adjusted for assumed age distribution <sup>d</sup>
Anchovies	Egg	1.470E+09	2.016E+09	0	0
	Larva	2.010E+09	4.017E+09	0	0
	Age 0+	0	0	0	0
	Age 1	0	0	2.700E+06	1.414E+07
Blennies	Egg	0	0	0	0
	Larva	5.070E+09	9.316E+09	0	0
	Age 0+	0	0	0	0
	Age 1	0	0	1.090E+03	3.287E+03
<i>Cancer crabs</i>	Egg	0	0	0	0
	Larva	3.070E+10	6.140E+10	0	0
	Age 0+	0	0	0	0
	Age 1	0	0	1.120E+05	1.120E+06
Gobies	Egg	0	0	0	0
	Larva	5.480E+09	1.002E+10	0	0
	Age 0+	0	0	0	0
	Age 1	0	0	3.670E+04	2.060E+05
California Halibut	Egg	0	0	0	0
	Larva	9.380E+06	1.715E+07	0	0
	Age 0+	0	0	0	0
	Age 1	0	0	3.100E+03	4.340E+03
Rockfishes	Egg	0	0	0	0
	Larva	0	0	0	0
	Age 0+	2.710E+08	5.206E+08	0	0
	Age 1	0	0	9.450E+04	7.381E+05
Surfperches	Egg	0	0	0	0
	Larva	0	0	0	0
	Age 0+	0	0	0	0
	Age 1	0	0	4.080E+05	2.133E+06

- a. Total of mean annual losses at sixteen facilities providing records of entrainment loss rates.
- b. Includes consideration of uncertainty about precise ages (see definition of  $S^*_j$  in Section 2.1.1).
- c. Total of mean annual losses at eighteen facilities providing records of impingement loss rates.
- d. Reported loss rates were assumed to be comprised of individuals ranging in age from one to five years, with the age frequency distribution corresponding to the modal age-specific mortality rates of each species group (U.S. EPA 2004); here the derived distribution of loss frequencies are re-expressed as age 1 equivalents.

### 2.4.1 Adjusting Empirical Loss Rates to Account for Uncertainty About Age Distribution

Organisms collected to quantify impingement and entrainment rates are typically categorized by life stage, and more detailed descriptions of the age of the organism (e.g., age in days) are not provided. Although in some cases researchers have used more detailed staging schemes such as categorizing larvae as yolk-sac or post yolk-sac, we have interpreted empirical loss records according to a standardized staging scheme in the sequence egg, larva, age 0+, age 1, age 2, etc. This method sacrifices a certain amount of detailed information, but it allows us to standardize disparate studies. Regardless of the level of detail in the staging scheme, the precise age of killed organisms is unknown. Our analysis accounts for that uncertainty by assuming that killed organisms include a range of ages spanning the entire stage. This assumption leads to use of the scaling factor  $S^*$  in Equation 1, which we apply to all empirical loss rates.

For impingement losses we have additionally used the assumption of the EPA (U.S. EPA 2004) that impingement losses affect individuals of age 1 through age 5 in proportions relative to species-specific mortality rates, so we adjusted empirical impingement loss rates by species-specific factors to convert losses with the assumed age distribution into losses expressed as age 1 equivalents using methods and parameter values from U.S. EPA (2004).

## 2.5 Selection of Representative Species

As noted above, we performed our sensitivity analyses on species identified as most vulnerable to impingement and entrainment, with high ecological and/or economic value, and representing a diversity of life history types. Table 3 lists the species and species groups selected for analysis and the selection criteria for each group.

Including anchovies in our analysis provided us an opportunity to investigate impingement and entrainment impacts on a relatively short lived, highly fecund fish species. Anchovy spawning behavior entails broadcast dispersal of eggs into coastal currents. This causes anchovies to be vulnerable to entrainment.

California's goby species spend their entire life cycle in the same coastal environments where impingement and entrainment occurs. As such, they make up a substantial portion of impingement and entrainment samples. Despite being short lived and moderately fecund, they can be locally abundant, providing an important forage base to predatory species.

California's blenny species are similar to gobies, except that blennies tend to be smaller and live longer. Blennies have no commercial or recreational fisheries in California. Inclusion of blennies in our analysis provided us an opportunity to investigate a species that experiences impingement and entrainment losses but is not well studied.

**Table 3: Selection criteria for species included in the sensitivity analysis**

<b>Species</b>	<b>Reason for inclusion</b>
Anchovies	One of the most common impingement and entrainment species. Short lived and highly fecund. Can be a close surrogate for other bait/forage fish species. Commercially harvested.
Gobies	Ecologically important forage species. Data poor life history parameters. Locally abundant in bays and estuaries where impingement and entrainment occurs. Occur in large numbers and high frequency in southern California facilities impingement and entrainment samples. Allows contrast with blennies that share similar characteristics.
Blennies	Ecologically important forage species. Data poor life history parameters. Locally abundant in bays and estuaries where impingement and entrainment occurs. Occur in large numbers and high frequency in southern California impingement and entrainment samples. Allows contrast with gobies that share similar characteristics.
<i>Cancer</i> spp. crabs	Commercially and recreationally harvested. Complicated early life history.
California halibut	Ecologically important predator species. Utilize bays and estuaries where impingement and entrainment occurs. Commercially and recreationally harvested.
Rockfishes	Estimates of life history parameter values available. Very long lived and fecund. Stocks are very depressed from historic levels. Commercially and recreationally harvested.
Surfperches	Unique life history. Occurs in southern California impingement and entrainment samples. Recreationally harvested.

Inclusion of *Cancer* spp. provides an invertebrate species with a complicated life history that is highly affected by environmental conditions. Natural environmental variability in ocean temperatures and currents can have a substantial effect on ELS mortality. As such, very few crabs survive to settlement. Most successful settlement occurs in coastal bays and estuaries where most of California's impingement and entrainment occurs. Life history parameters of Dungeness crab (*Cancer magister*) were used to represent the genus.

California halibut are a long-lived, highly fecund species. Life history adaptations, which may include use of estuarine habitat for ELS rearing, and their relatively small home range, indicate potential vulnerability to impingement and entrainment. Adult halibut are subject to commercial and recreational fisheries (Allen 1990).

Examining rockfishes as a group enabled us to evaluate a long lived, highly fecund species for which estuarine habitat is often less critical for ELS survival than it is for California halibut. Rockfishes are also distinguished from the other species considered by being relatively less dependent on estuarine habitats and are therefore at higher risk of entrainment or impingement in marine intakes, (e.g., the Diablo Canyon power plant) (Raimondi et al. 2005).

Inclusion of surfperches provided a short lived, low fecundity species for our analysis. Once-through cooling water facilities draw water from habitat used throughout the life cycle of surfperch, which puts them at risk of impingement.

A detailed listing of individual species included in each of the species groups described above and a listing of all other species reported among impingement and entrainment losses in California are provided in Appendix A.

## **2.6 Life History Data Assembly**

We organized the major life history parameters for the selected species into a common database. The database includes mortality estimates (natural, fishing, and total), point estimates of species fecundity, and age/length relationships.

In our review of life history data, we obtained a large amount of species-specific life history data from various literature sources, beginning with life history data used in EPA's section 316(b) rulemaking (U.S. EPA 2004). Information available varied by species. Some species such as rockfishes had multiple mortality and fecundity values for all life stages, while others such as blennies, had none or few. Fecundity and growth data were obtained for all species and did not represent a substantial data gap. Approximately 200 references were reviewed in this process, including sources cited in documents we reviewed (see Appendix A). The sets of vital rate values we assembled by this process are not intended to be a complete or definitive representation of the available data, and it is likely some relevant publications were not reviewed. The assembly of parameter values used in the sensitivity analysis involved integration of information from multiple sources. We believe the values we have assembled are adequate and useful for characterizing the sensitivity of the demographic models to uncertainty in vital rates, without reference to any particular application of the models. Readers who require estimates of vital rates for other particular applications are advised to independently identify values that are most relevant for their purposes.

References that reported variability estimates such as confidence intervals or standard errors provided within-study variability. Multiple references for a single species parameter provided between-study variability. These two sources of variability can potentially capture the range of a given life history parameter associated with natural variability within a studied community, temporal changes, or geographic differences within and between studied communities. Geographical differences in life histories are very important to characterize because of California's extremely diverse coastal environment and fish and invertebrate communities.

We also examined the following databases for pertinent literature: Biosis, Aquatic Sciences and Fisheries Abstracts, Oceanic Abstracts, Wilson Biological and Technical Abstracts, National Technical Information Service, Dissertation Abstracts, and Inside Conferences. Our search strategy was based on six sets of life history criteria in conjunction with a set of seven species or species groups (Table 4). Results were then screened for relevancy prior to adding into our life history database.

**Table 4: External literature database search strategy criteria**

<b>Type of information</b>	<b>Terms used as keywords in automated literature search</b>
Life history criteria	Mortality or fecundity or survival. Population dynamics or reproductive dynamics. Life history. Recruitment or abundance or distribution. Hatching success or reproductive success (age and growth). (length and weight). (age and length). (age and weight).
Species or species groups	Northern anchovy. goby or gobies. Dungeness crab. blenny or blennies. California halibut. rockfishes ( <i>Sebastes</i> ). surf perch or surfperch.

In the literature that we reviewed, values for key life history parameters varied widely. None of the individual reports that we found provided a complete set of values for the required parameters. In addition, many life history parameters were reported for life stages that were poorly defined or undefined. Examples of such data include reported mortality values for a species “at fisheries recruitment” or “adult mortality.” If the authors did not report enough information for us to derive a common life stage or age, we relied on additional sources of information to make simplifying assumptions.

Data gathering and extrapolation steps involved organizing and documenting life history data into a common database and using reported information to fill in needed parameters. Missing parameters included instances where stage durations were not reported, calculation of total mortality by adding natural and fishing mortalities, and computing daily total mortality/survival rates. When necessary to fully exploit information found in the literature, we relied on simplifying assumptions such as inferring that adult mortality rates should be applied to all ages greater than species age at first maturity, using general life stage durations to calculate daily mortality when not provided by the author(s), and assuming that fishing mortality was zero for life stages/age classes prior to entering respective fisheries. When a life history trait was reported as “less than” or “greater than” a particular age, the value was assigned to all age classes in that set.

A number of steps were involved in organizing the life history data. First, data were organized so that repeat entries could be removed. This occurred when more than one author cited the same life history parameter. When authors reported male and female specific life history parameters both were retained. After duplicate entries were removed, the minimum, mean (or median), and maximum values for each life history stage were identified. For certain species with few minimum or maximum values, the calculated minimum or maximum was greater or less than the mean value. In these cases a simple ratio of the reported minimum and maximum to the mean (or median) value was used to for the final generalized life history estimates. The values identified as the mean (or median) were subsequently used as the modal value in random selection from a statistical distribution in Monte Carlo simulations (see Section 2.3.2).

We filled in missing life history using data for a related species, extrapolating life history values past reported age classes when necessary, and defining the minimum and maximum values so

that they were symmetric around the modal value. The net result of the literature review was a life history table with parameter values for each the seven species groups we analyzed (described in Sections 3.1.1-3.1.7).

# CHAPTER 3:

## Project Outcomes

### 3.1 Modeled Life Histories

In this section we present the generalized life history tables for each species evaluated in the sensitivity analysis and comment on how the parameters and data selected relate to the ecology of each species.

#### 3.1.1 Anchovies

The northern anchovy is one of the approximately 139 species in the family Engraulidae (Moser 1996). Northern anchovy are small pelagic schooling fish found in surface waters down to depths of 300 meters (m) (Virginia Tech 1998). They obtain food by filtering plankton from the water column, including euphausiids, copepods, and decapod larvae, such as larvae of Cancer crabs (PFMC 1998). The maximum age for northern anchovy is seven years and the maximum length is 229 mm (Froese and Pauly 2007).

Essentially every predatory fish, bird, and mammal in the California Current preys upon northern anchovy (Kucas 1986). Researchers have observed that breeding success in marine birds are linked to anchovy abundance (PFMC 1998). Because commercially and recreationally important species rely on anchovy, their abundance as a food source is important to these fisheries.

Anchovy spawning is heaviest between Point Conception and Baja California, within about 100 km of the coast in water less than 10-m deep when water temperatures are 12 to 15°C (Kucas 1986). Although anchovy can spawn throughout the year, most spawning occurs in winter and spring, peaking in the summer months in the northern extension of their range. They are batch spawners (Froese and Pauly 2007), with females dispersing eggs without parental care during development. Kucas (1986) reports that a single female may produce as many as 30,000 eggs in a year. In female anchovy, sexual maturity is usually reached at about the end of their first year, when they are just less than 100 mm in length. All anchovies are mature in their second year of life. Once fertilized, pelagic anchovy eggs hatch in two to four days, after which larvae develop in the food-rich epipelagic zone, where they remain through sexual maturity. Coastal bays and estuaries offer shallow, productive, food-rich environments that are ideal for anchovy development, but larvae are vulnerable to cooling water intakes located in such areas.

Northern anchovy are exploited in both a reduction fishery, where landings are converted to fish meal, and a bait fishery, where captured fish are kept alive for direct sale to anglers. Stock biomass estimates are unavailable for recent years but, based on abundance index data, the stock is thought to be stable at a modest biomass level (Bergen and Jacobson 2001).

The results of our literature review of anchovy life history parameters and our interpretations of available information for the purposes of the sensitivity analysis are summarized in Table 5. The mortality and fecundity estimates we selected for northern anchovy agree with their life history

in California coastal fish communities. Lifetime fecundity estimates are moderately high compared to other fish in our analysis. This corresponds well to the fact that anchovy mature at an early age and can spawn multiple times in a given year. The egg and larvae mortality rates are relatively high and variable, as may be expected a species that broadcasts eggs into coastal currents without parental care. Furthermore, these life stages are vulnerable to intense predation.

### 3.1.2 Gobies

California has 12 native and four nonnative goby species (Swift 2001). Of the native gobies, bluebanded goby (*Lythrypnus dalli*), zebra goby (*Ptereleotris zebra*), and blackeye goby (*Coryphopterus nicholsi*) are marine species that occur in association with hard substrates. The tidewater goby (*Eucyclogobius newberryi*) is listed as endangered in California (USFWS 2006). Longjaw mudsucker (*Gillichthys mirabilis*), arrow goby (*Clevelandia ios*), bay goby (*Lepidogobius lepidus*), shadow goby (*Yongeichthys nebulosus*), cheekspot goby (*Ilypnus gilberti*), tidewater goby, and longtail goby (*Ctenogobius sagittula*) are predominantly bay, estuarine, and brackish water species. This makes them vulnerable to impingement and entrainment where cooling water intake structures withdraw water from the water bodies where they occur.

Gobies are generally less than 200 mm in length and four years of age (Brothers 1975). They have one of two life history strategies. Smaller species mature early, spawn multiple times, and have an almost complete annual turnover of the population. Larger species mature later, spawn less frequently, and live multiple years (Swift 2001). Smaller species with mostly annual life histories include arrow gobies and tidewater gobies. Mudsucker and the non-native yellowfin goby (*Acanthogobius flavimanus*) can grow larger and live longer.

Gobies have a unique reproductive strategy among fish studied in this report. Eggs are laid in burrow or crevice nests that are guarded by males. Sticky filaments on club shaped eggs attach to rock or sand within the nests. Nests may contain hundreds to thousands of eggs that typically hatch between five and ten days after fertilization depending on size and species (Swift 2001).

Once hatched, larvae leave the burrow and are planktonic. Planktonic larvae are vulnerable to entrainment. Little is known of the larval duration but it is probably a month or less. Larvae settle to live on or in the substrate for the remainder of their life cycle. Adult goby home ranges vary from their burrow to the entire embayment or estuary where they are located (Swift 2001).

**Table 5: Age specific instantaneous mortality rates and lifetime fecundity used in sensitivity analysis of various loss metrics for assessing impingement and entrainment impacts in California for anchovies**

Age class	Total mortality rate (Z)			Fishing mortality rate (F)			Weight (g) <sup>a</sup>	Fecundity (eggs/lifetime)		
	Minimum	Modal	Maximum	Minimum	Modal	Maximum		Minimum	Modal	Maximum
Egg	0.624	0.781	0.937	0.000	0.000	0.000	-			
Larva	5.856	7.320	8.784	0.000	0.000	0.000	-			
Age 0+	0.282	0.352	0.423	0.000	0.000	0.000	-			
Age 1	1.015	1.107	1.199	0.091	0.182	0.272	18.5			
Age 2	0.860	1.380	1.900	0.148	0.296	0.445	24.0			
Age 3	0.952	1.567	2.182	0.182	0.364	0.546	27.6			
Age 4	1.148	1.703	2.258	0.163	0.326	0.490	31.0			
Age 5	1.421	1.840	2.258	0.163	0.326	0.490	34.6			
Age 6	1.695	1.977	2.258	0.163	0.326	0.490	35.8			
Lifetime	-	-	-	-	-	-	-	13,743	37,800	61,857

a. Weights for age classes not subject to fishing mortality are not pertinent to the FY model.

Gobies play an important ecological role in California's coastal fish communities. They transfer energy from the lowest level of the food chain upward to top predators, including fish species with commercial and recreational value such as California halibut and striped bass (*Morone saxatilis*). Harbor seals (*Phoca vitulina*) and shore birds also feed on gobies. Aside from being important forage fish, gobies have some value in the aquarium trade and in educational displays.

The mortality and fecundity estimates used in our analysis for goby indicate that they experience high mortality as larvae and moderate mortality in later adult age classes. Given that these species practice egg guarding, egg mortality would be expected to be low. Once hatched larvae leave the nest, they are planktonic and have no protection from predation or currents that could potentially transport them away from suitable settlement habitat (Brothers 1975). Once settled in a suitable habitat, adult goby are likely to have lower mortality rates than pre-settled larvae. While lower than earlier life stages, adult mortality rates are still moderate, potentially reflecting their ecological role as important forage for large fish species. Relatively small lifetime fecundity estimates could be an artifact of high mortality rates and moderate to low fecundity. This could also reflect of habitat limitation and predation mortality.

The results of our literature review of goby life history parameters and our interpretations of available information for the purposes of the sensitivity analysis are summarized in Table 6.

### **3.1.3 Crabs**

Crabs in the genus *Cancer*, particularly Dungeness crab, are commercially-important species in northern California, and are ecologically important as both predator and prey at all life stages.<sup>2</sup> Although distributed along the entire California coast, Dungeness crab are only present in commercially harvestable numbers north of Point Conception (Pauley et al. 1989).

Dungeness crab inhabit coastal intertidal waters to a depth of at least 180 m. They prefer mud, eelgrass, or sandy substrates and prey upon clams, crustaceans, and fish. In California, mating occurs annually from March to July when adult crabs move to nearshore coastal locations. From September to November females use sperm stored in spermathecae to fertilize extruded eggs. Extruded eggs are attached to the female and cared for until hatching. Dungeness crab are relatively fecund, as a female crab may produce up to two million eggs in a single brood (Wild 1983a).

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<sup>2</sup>. In this study we have used life history characteristics of Dungeness crab to conduct the sensitivity analysis and we have used impingement and entrainment losses of all *Cancer* spp. to represent statewide loss rates in California.

**Table 6: Age specific instantaneous mortality rates and lifetime fecundity used in sensitivity analysis of various loss metrics for assessing impingement and entrainment impacts in California for gobies**

Age class	Total mortality rate (Z)			Fishing mortality rate (F)			Weight (g) <sup>a</sup>	Fecundity (eggs/lifetime)		
	Minimum	Modal	Maximum	Minimum	Modal	Maximum		Minimum	Modal	Maximum
Egg	0.230	0.288	0.345	0.000	0.000	0.000	–			
Larva	1.444	2.361	3.279	0.000	0.000	0.000	–			
Age 0+	0.550	0.916	1.283	0.000	0.000	0.000	–			
Age 1	1.196	1.269	1.342	0.000	0.000	0.000	–			
Age 2	1.196	1.269	1.342	0.000	0.000	0.000	–			
Age 3	1.196	1.269	1.342	0.000	0.000	0.000	–			
Age 4	1.196	1.269	1.342	0.000	0.000	0.000	–			
Age 5	1.196	1.269	1.342	0.000	0.000	0.000	–			
Age 6	1.196	1.269	1.342	0.000	0.000	0.000	–			
Age 7	1.196	1.269	1.342	0.000	0.000	0.000	–			
Lifetime	–	–	–	–	–	–	–	333	467	601

a. Gobies are not subject to fishing mortality, so weight values, used in the FY model, are not needed.

Water temperature has a considerable influence on the rate of egg development and mortality after fertilization and spawning (Pauley et al. 1989). When temperatures rise, the rate of egg development also rises, but so does the rate of mortality. Depending on local environmental conditions, hatching occurs 60 to 120 days post fertilization. In central California this usually occurs from late December to early February, and in northern California it occurs from January to early March. Once hatched, Dungeness crab begin a complicated life cycle.

Developing Dungeness crab passes through five zoeal stages and one megalopal stage after hatching (Reilly 1983). All zoeal stages are entirely planktonic, meaning that they are unable to swim against ocean currents. The megalopa is the final larval stage and is planktonic until settling to the bottom and molting to the first post-larval instar. In California, larval crab are planktonic for 105 to 125 days (Reilly 1983). The larval stage crab range in length (tip of rostral spine to end of telson) from approximately 2.5 mm for stage I zoeae up to 11.0 mm for megalopae (Poole 1966; as cited in Wild and Tasto 1983). Juveniles molt 11 to 12 times before sexual maturity (Butler 1960; as cited in Wild and Tasto 1983) which can take up to 2 years. At maturity, carapace width is about 116 mm for males and 100 mm for females.

The stages of development, time to development stage, and general distribution patterns of Dungeness crab development stages in California are summarized in Table 7. Stage duration estimates are based on the first appearance of larval and juvenile crabs in a multiyear geographic distribution study in central and northern California (Reilly 1983) and estimates made by Wild (1983b), Pauley et al. (1989), and Hankin and Warner (2001). The length of the larval period from post-hatch to juvenile was approximately 105 to 125 days. Approximately 150 days are required to complete the five zoeal stages and the remaining 25-90 days are spent in the megalopal stage.

**Table 7: Summary of crab development stage/stage durations and occurrences used in this study**

<b>Stage</b>	<b>Average stage duration (days)</b>	<b>Age (days)</b>	<b>Date first observed<sup>a</sup></b>	<b>Reference</b>
Egg	110	110	October-January	Wild 1983b
Egg	60-90			Pauley et al. 1989
Zoea 1	15	125	12-December	Moloney et al. 1994
Zoea 2	20	145	6-January	Moloney et al. 1994
Zoea 3	29	174	6-January	Moloney et al. 1994
Zoea 4	40	213	23-January	Moloney et al. 1994
Zoea 5	66	279	15-February	Moloney et al. 1994
Megalopal	91	370	6-March	Moloney et al. 1994
Megalopal	25-30			Pauley et al. 1989
Larvae	105-125	225		Hankin and Warner 2001
Juvenile	280	505		Hankin and Warner 2001
Mature adult		730		Hankin and Warner 2001

a. Reilly 1983.

Spatial distributions of young Dungeness crab are life stage dependent, with zoeal and pre juvenile megalopae found outside embayments and juveniles closer to shore and in bays. Because eggs are attached to females, newly hatched zoea are found along the California coast and not in embayments. Therefore, it is hypothesized that zoeal stage crab distribution is dependent on ocean currents where hatched. This is a well-studied, but poorly understood phenomenon (Reilly 1983).

Stage I zoeae conduct diel vertical migrations and are more abundant at the surface at night and at 15- and 25-m depths by day. Horizontal dispersal is evident during the early zoeal stages. Early larval crab are also readily transported by offshore currents. The lack of information to fully characterize larval crab planktonic distributions and subsequent megalopae near shore settlement is a major data gap in understanding natural mortality in early life stage (Reilly 1983).

Dungeness crab larvae in central California hatch and complete their early zoeal development during the time of the Davidson Current (November to February). The strength of this counter current is evident by considerable offshore movement of larvae occurring during zoeal stages II-V (Reilly 1983).

In central California, the arrival of megalopae in near shore waters generally occurs in April, during the time of upwelling caused by the predominant California current. From April to June, winds blow predominantly from the northwest and due to Ekman transport that drives surface currents offshore and deep bottom currents onshore. This period coincides with the concentration of settled benthic dwelling juvenile crab in nearshore gulf and bay habitats (Reilly 1983).

Once settled in near shore habitats, juvenile crabs feed and grow in productive shallow waters. At this point in their development they are morphologically similar to adult crab. They feed on crustaceans and mollusks until they reach about 60 mm carapace width then prey on fish and *Cragon* shrimp (Pauley et al. 1989). Crabs usually migrate to deeper coastal waters at 1.5-2 years of age when they enter the adult population (Collier 1983; Hankin and Warner 2001).

Crabs are subject to intense predation at all stages of early development, often starting before embryos hatch, and are also cannibalistic. Age-specific crab mortality rates are the highest among the species in our analysis and may be artifacts of the complicated crab life cycle and lack of referenced age 1+ mortality rates. Nonetheless, it is known that substantial mortality occurs in crab early life stages, depending on factors such as excessively high or low water temperatures, water temperature fluctuations, currents affecting early life stage distribution and subsequent settlement, and heavy predation. Mortality rates of juvenile crab are not well supported in the literature. However, given that juvenile crab are heavily preyed upon after settlement, we extrapolated the high larval rates to this life stage.

The results of our literature review of crab life history parameters and our interpretations of available information for the purposes of the sensitivity analysis are summarized in Table 8.

**Table 8: Age specific instantaneous mortality rates and lifetime fecundity used in sensitivity analysis of various loss metrics for assessing impingement and entrainment impacts in California for crabs**

Age class	Total mortality rate (Z)			Fishing mortality rate (F)			Weight (g) <sup>b</sup>	Fecundity (eggs/lifetime)		
	Minimum	Modal	Maximum	Minimum	Modal	Maximum		Minimum	Modal	Maximum
Egg	0.208	0.595	0.981	0.000	0.000	0.000	–			
Larva <sup>a</sup>	9.185	11.839	14.493	0.000	0.000	0.000	–			
Age 1	7.185	9.839	12.493	0.000	0.000	0.000	–			
Age 2	0.608	2.155	3.701	0.080	1.625	3.171	458			
Age 3	1.110	3.110	5.110	0.999	2.799	4.599	848			
Age 4	0.256	0.590	0.924	0.128	0.461	0.794	1,363			
Age 5	0.256	0.590	0.924	0.128	0.461	0.794	1,579			
Age 6	0.256	0.590	0.924	0.128	0.461	0.794	1,768			
Age 7	0.256	0.590	0.924	0.128	0.461	0.794	2,359			
Age 8	0.256	0.590	0.924	0.128	0.461	0.794	2,554			
Age 9	0.256	0.590	0.924	0.128	0.461	0.794	2,758			
Age 10	0.256	0.590	0.924	0.128	0.461	0.794	2,974			
Lifetime	–	–	–	–	–	–	–	318,976	1,159,488	2,000,000

a. Larval stage in crab life history model includes all zoeal and megalopae stages and represents the period designated as age 0+ for other species.

b. Weights for age classes not subject to fishing mortality are not pertinent to the FY model.

### 3.1.4 Blennies

Bay blenny (*Hypsoblennius gentiles*), rockpool blenny (*Hypsoblennius gilberti*), and mussel blenny (*Hypsoblennius jenkinsi*) inhabit California's coastal waters, estuaries, and bays (Craig and Pondella 2004; Allen et al. 2006). These species often inhabit clam burrows, worm tubes, and mussel beds. Bay blenny are found in intertidal shallows where they feed on small benthic invertebrates and algae (Froese and Pauly 2007).

Bay blenny can reach 15 cm in length and can live up to 7 years. Rockpool blenny have a similar life history as bay blenny except they can attain a greater length (17 cm) and live up to 9 years. Mussel blenny are a similar but smaller and shorter-lived species, only reaching 13 cm in length with a maximum reported age of 6 years (Froese and Pauly 2007).

Life histories are similar to gobies, although blennies tend to have longer life expectancy and higher lifetime fecundity. Like gobies, blennies are oviparous, have adhesive eggs that are attached to the walls of the nest, and guard their eggs. The spawning season of the three California *Hypsoblennius* species begins in the spring and may extend into September (Stephens et al. 1970). Females spawn three to four times over a period of several weeks and the number of eggs a female produces varies proportionately with her size.

The results of our literature review of blenny life history parameters and our interpretations of available information for the purposes of the sensitivity analysis are summarized in Table 9.

### 3.1.5 California Halibut

California halibut are most abundant between San Francisco Bay and Magdalena Bay, but occur as far north as the Quillayute River in Washington (Kucas and Hassler 1986) and as far south as Baja California (Moser and Watson 1990). Distribution varies throughout its range according to life history stage and time of year. For example, adults mostly inhabit coastal continental shelf waters from 40 to 100 m deep, but mature halibut (females > 420 mm in length, males > 230 mm) move from offshore waters into shallow coastal waters to spawn at depths of 5 to 18 m (Young 1960; as cited in Kucas and Hassler 1986). California halibut spawn throughout the year, primarily in February and March and secondarily between July and October off California and northern Baja California (Moser and Watson 1990).

California halibut are highly fecund and are broadcast spawners, meaning that gametes are fertilized externally and develop without parental care (Allen 1990). Caddell et al. (1990) reported between 5 and 13 spawns per season, for a total of between 1.5 and 7.6 million eggs per female each spawning season. The estimated lifetime fecundity for California halibut is 9.8 million eggs (Caddell et al. 1990). Like most broadcast spawners, fecundity is proportional to body size. When released, halibut eggs are 0.7-0.8 mm in diameter and pelagic (Allen 1988; as cited in Haugen 1990).

Nine stages in development during the first two months after hatching have been defined for California halibut (Gadomski et al. 1990). The most substantial change occurs approximately one month after hatching, when metamorphosing larvae (7.5-9.4 mm in length) begin settling to the bottom (Kramer 1990).

**Table 9: Age instantaneous mortality survival rates and lifetime fecundity used in sensitivity analysis of various loss metrics for assessing impingement and entrainment impacts in California for blennies**

Age class	Total mortality rate (Z)			Fishing mortality rate (F)			Weight (g) <sup>a</sup>	Fecundity (eggs/lifetime)		
	Minimum	Modal	Maximum	Minimum	Modal	Maximum		Minimum	Modal	Maximum
Egg	0.084	0.105	0.126	0.000	0.000	0.000	–			
Larva	1.697	2.425	3.152	0.000	0.000	0.000	–			
Age 0+	0.550	0.916	1.283	0.000	0.000	0.000	–			
Age 1	0.462	0.605	0.748	0.000	0.000	0.000	–			
Age 2	0.462	0.605	0.748	0.000	0.000	0.000	–			
Age 3	0.462	0.605	0.748	0.000	0.000	0.000	–			
Age 4	0.462	0.605	0.748	0.000	0.000	0.000	–			
Age 5	0.462	0.605	0.748	0.000	0.000	0.000	–			
Age 6	0.462	0.605	0.748	0.000	0.000	0.000	–			
Age 7	0.462	0.605	0.748	0.000	0.000	0.000	–			
Lifetime	–	–	–	–	–	–	–	17,912	65,111	112,310

a. Weights for age classes not subject to fishing mortality are not pertinent to the FY model.

Small juveniles are most abundant in bays and estuaries (Kramer 1990). Once juveniles have grown to between 18 and 22 cm total length (at 1 to 2 years of age), they migrate from protected nursery areas to deeper areas of the coast (Ish and Stoman 2006). Soon after, they are recruited into the coastal fishery, after which fishing mortality increases the rate of total mortality (Kramer 1990; Ish and Stoman 2006).

The results of our literature review of halibut life history parameters and our interpretations of available information for the purposes of the sensitivity analysis are summarized in Table 10.

### 3.1.6 Rockfishes

There are approximately 60 species of *Sebastes* rockfishes in California waters that support important commercial and sport fisheries (Stein and Hassler 1989). Of these, 17 species have been identified in California impingement and entrainment studies, though this number could be greater given that rockfishes are rarely identified to the species level in impingement and entrainment samples. Rockfishes inhabit a wide variety of different habitats, from shallow and deepwater reefs to open oceans, and are a major component of many California reef communities (Allen et al. 2006).

*Sebastes* rockfishes are long-lived, and most species mature between three and 10 years. Some of the longer lived species, such as yelloweye rockfishes and shortspine thornyhead, have been aged to over 100 years, although most maximum ages are reported between 20 and 60 years (Burton et al. 2000; Alaska Department of Fish and Game 2007).

Rockfishes in the genus *Sebastes* are distinctive because they are viviparous livebearers, which means that embryonic development occurs within parental fish and young are released as 5 to 6 mm long individuals (Stein and Hassler 1989).

Young rockfishes are pelagic for several months to a year, and are abundant and widely distributed in the California Current (Yoklavich et al. 1996). Settlement usually occurs in or near some structure, such as kelp beds or shallow and deep reefs, in coastal bays and estuaries.

Early life stages have high mortality rates as a result of predation and fluctuations of favorable growth conditions. Successful settlement to a benthic existence can also influence mortality rates. Post-settlement age classes have greater chance of survival as reflected in lower mortality rates, but are soon recruited into California's groundfish fisheries, where mortality is high.

Fishing mortality is a major mortality factor for adult age classes. Given the long history of commercial and recreational fishing for rockfishes in California, most stocks are only a fraction of historic levels, and many stocks can no longer support commercial fishing. Additionally, landings are composed of smaller than average fish, often harvested before maturity (PMCC 1999).

**Table 10: Age specific instantaneous mortality rates and lifetime fecundity used in sensitivity analysis of various loss metrics for assessing impingement and entrainment impacts for California halibut**

Age class	Total mortality rate (Z)			Fishing mortality rate (F)			Weight (g) <sup>a</sup>	Fecundity (eggs/lifetime)		
	Minimum	Modal	Maximum	Minimum	Modal	Maximum		Minimum	Modal	Maximum
Egg	0.112	0.223	0.335	0.000	0.000	0.000	-			
Larva	1.181	2.363	3.544	0.000	0.000	0.000	-			
Age 0+	0.011	0.012	0.014	0.000	0.000	0.000	-			
Age 1	0.090	0.192	0.294	0.000	0.000	0.000	-			
Age 2	0.090	0.192	0.294	0.000	0.000	0.000	-			
Age 3	0.090	0.192	0.294	0.000	0.000	0.000	-			
Age 4	0.090	0.192	0.294	0.000	0.000	0.000	-			
Age 5	0.090	0.192	0.294	0.000	0.000	0.000	-			
Age 6	0.256	0.512	0.768	0.080	0.160	0.240	4,031			
Age 7	0.256	0.512	0.768	0.080	0.160	0.240	5,551			
Age 8	0.256	0.512	0.768	0.080	0.160	0.240	6,950			
Age 9	0.256	0.512	0.768	0.080	0.160	0.240	8,567			
Age 10	0.256	0.512	0.768	0.080	0.160	0.240	9,645			
Age 11	0.256	0.512	0.768	0.080	0.160	0.240	10,809			
Age 12	0.256	0.512	0.768	0.080	0.160	0.240	12,063			
Lifetime	-	-	-	-	-	-	-	4,262,000	9,788,000	15,314,000

a. Weights for age classes not subject to fishing mortality are not pertinent to the FY model.

Rockfishes are unique among our species of interest, being highly fecund and relatively long lived. Yearly fecundity estimates are variable, with estimates ranging from a low of 1,200 and a high of 5.4 million (MacGregor 1970; as cited in Burton et al. 2000).

The results of our literature review of rockfishes life history parameters and our interpretations of available information for the purposes of the sensitivity analysis are summarized in Table 11.

### 3.1.7 Surfperches

There are 19 species of surfperches found in coastal waters of California (CDFG 2007a). The most common species are silver surfperch (*Hyperprosopon ellipticum*), walleye surfperch (*Hyperprosopon argenteum*), shiner perch (*Cymatogaster aggregata*), redbtail surfperch (*Amphistichus rhodoterus*), rubberlip perch (*Rhacochilus toxotes*), and barred surfperch (*Amphistichus argenteus*). All of these species are important sportfish in California (Fritzsche and Collier 2001).

Surfperches are relatively small, demersal, short lived fish found in a variety of marine habitats, including sandy beaches, rocky substrates, and kelp beds (Ryan et al. 2004). The maximum age averages six to seven years (Fritzsche and Collier 2001). Most species reach maturity by age 2 (Lane et al. 2002). They are preyed upon as young and adults by larger fish such as kelp bass (*Paralabrax clathratus*), barred sand bass (*Paralabrax nebulifer*), California halibut, rockfishes, and salmon, as well as most piscivorous birds and mammals (Ryan et al. 2004).

California surfperch belong to the Embiotocidae family of fishes. Like *Sebastes* rockfishes, embiotocids are viviparous, and female surfperches give birth to well-developed young, which have a better chance of survival (Ryan et al. 2004). This is reflected in age 0+ mortality rates that are the lowest in our study (Table 12).

Because of the maternal energy contribution to developing young and relatively small size, embiotocid species have relatively small broods compared to most marine fishes. The average brood size ranges from 5 to 113 young, depending on maternal size and species. Some species aggregate to mate, and female surfperches often move into shallow coastal waters or bays and estuaries to give birth (Ryan et al. 2004).

Lifetime fecundity estimates are the lowest of all species in our analysis (Table 12). This likely results from a combination of low fecundity and relatively high adult mortality. Surfperches are preyed upon by larger fish such as kelp bass, barred sand bass, California halibut, rockfishes, and salmon, as well as most piscivorous birds and mammals. In addition, there are both recreational and commercial fisheries for surfperches in California.

The results of our literature review of surfperches life history parameters and our interpretations of available information for the purposes of the sensitivity analysis are summarized in Table 12.

**Table 11: Age specific instantaneous mortality rates and lifetime fecundity used in sensitivity analysis of various loss metrics for assessing impingement and entrainment impacts in California for rockfishes**

Age class	Total mortality rate (Z)			Fishing mortality rate (F)			Weight (g) <sup>b</sup>	Fecundity (eggs/lifetime)		
	Minimum	Modal	Maximum	Minimum	Modal	Maximum		Minimum	Modal	Maximum
Age 0+ <sup>a</sup>	1.183	3.193	5.203	0.000	0.000	0.000	-			
Age 1	0.175	2.423	4.671	0.000	0.000	0.000	-			
Age 2	0.060	0.648	1.235	0.030	0.250	0.470	68.1			
Age 3	0.030	0.718	1.407	0.015	0.250	0.485	140			
Age 4	0.030	0.709	1.387	0.015	0.250	0.485	208			
Age 5	0.010	0.449	0.887	0.005	0.250	0.495	312			
Age 6	0.010	0.437	0.864	0.005	0.250	0.495	398			
Age 7	0.010	0.436	0.863	0.005	0.250	0.495	477			
Age 8	0.010	0.436	0.861	0.005	0.250	0.495	548			
Age 9	0.010	0.433	0.855	0.005	0.250	0.495	609			
Age 10	0.010	0.433	0.855	0.005	0.250	0.495	661			
Age 11	0.010	0.433	0.857	0.005	0.250	0.495	705			
Age 12	0.010	0.435	0.860	0.005	0.250	0.495	741			
Lifetime	-	-	-	-	-	-	-	104,145	191,470	278,795

a. Rockfishes are viviparous species and the age at birth for these species is defined as age 0+.

b. Weights for age classes not subject to fishing mortality are not pertinent to the FY model.

**Table 12: Age specific instantaneous mortality rates and lifetime fecundity used in sensitivity analysis of various loss metrics for assessing impingement and entrainment impacts in California for surfperches**

Age class	Total mortality rate (Z)			Fishing mortality rate (F)			Weight (g) <sup>b</sup>	Fecundity (eggs/lifetime)		
	Minimum	Modal	Maximum	Minimum	Modal	Maximum		Minimum	Modal	Maximum
Age 0+ <sup>a</sup>	0.640	1.280	1.920	0.000	0.000	0.000	–			
Age 1	0.640	1.280	1.920	0.000	0.000	0.000	–			
Age 2	0.383	0.765	1.148	0.070	0.140	0.210	56.8			
Age 3	0.294	0.588	0.882	0.140	0.280	0.420	92.3			
Age 4	0.805	1.609	2.414	0.140	0.280	0.420	119			
Age 5	0.805	1.609	2.414	0.140	0.280	0.420	136			
Lifetime	–	–	–	–	–	–	–	5	15	25

a. Surfperches are viviparous species and the age at birth for these species is defined as age 0+.

b. Weights for age classes not subject to fishing mortality are not pertinent to the FY model.

## 3.2 Sensitivity Analysis Results

For each of the assessment models analyzed (AEL, FH, FY), we conducted a sequence of distinct Monte Carlo calculations in which we varied all of the model parameters and then held individual parameters constant at a modal value. The modal value is the value that we identified from our literature review as the most likely value. The effect of holding a single parameter fixed on the distribution of model outputs of Monte Carlo simulations is illustrated in Figure 1 using the three models applied to entrainment of anchovies. In each panel of Figure 1, the narrower shape of the distinctive curve reflects the reduction in uncertainty that results from fixing the value of a selected parameter.

The rankings of each parameter (factor prioritization) were based on the values,  $V_i$ , that quantified the percentage of total uncertainty associated with each factor  $i$ . The CV was used to measure the relative precision of model results, with the CV given by the ratio of the standard deviation of model outputs (with selected conditions) and the point estimate determined with all parameters fixed at the modal values.

Results presented in Sections 3.2.1-3.2.3 are based on simulations where the assumed uncertainty about entrainment and impingement rates was set at +/-10 percent. Results presented in Section 3.2.4 describe a secondary set of analyses that used alternative assumptions about the degree of uncertainty about entrainment and impingement rates.

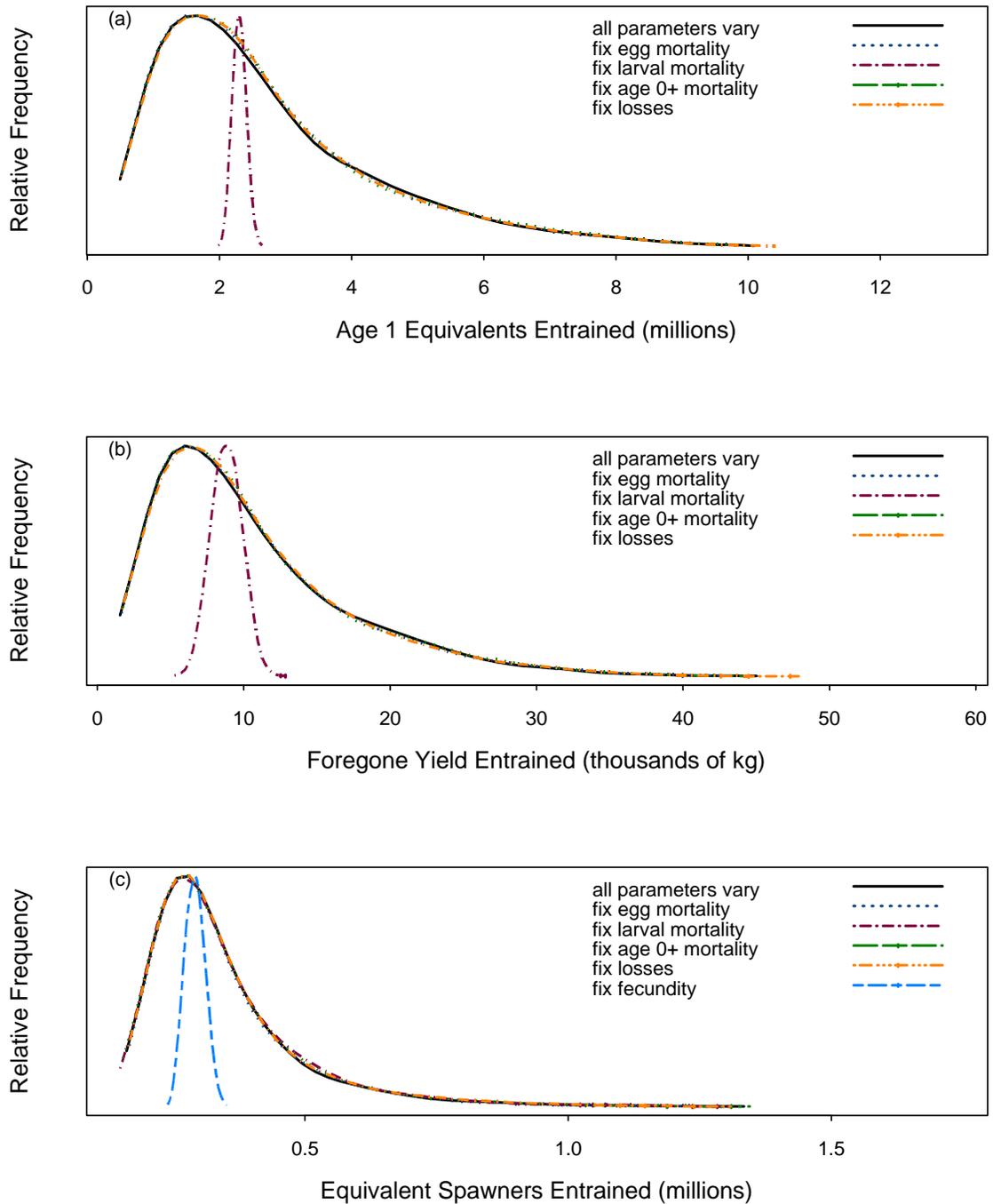
### 3.2.1 AEL Model

#### 3.2.1.1 Total Uncertainty

The CV of the AEL model applied to entrainment losses (Table 13) with all parameters variable ranged from 0.327 (for blennies) to 2.033 (for crabs). In other words, the standard deviation of the modeled uncertainty ranged from about 30 percent of the predicted point estimate for blennies to over 200 percent for crabs. The overall ranking of species groups from greatest precision to least precision as blennies > gobies > California halibut > anchovies > rockfishes > crabs. The CV of the AEL model applied to impingement losses (Table 14) with all parameters variable were substantially smaller, ranging from 0.041 (for crabs) to 0.224 (for rockfishes).

#### 3.2.1.2 Factor Prioritization

The parameter most influential to total uncertainty in entrainment calculations was the mortality rate of the larval stage for anchovies, blennies, California halibut, and crabs. For rockfishes, mortality rate of the age 0+ stage (the youngest stage for that species group) was most influential to total uncertainty (Table 13). For most species, the relative importance of other mortality rates was relatively negligible, except for gobies and blennies. For gobies and blennies, age 0+ mortality also contributed to total uncertainty. Uncertainty associated with entrainment rates was the greatest source of uncertainty for gobies.



**Figure 1: Distribution of model outcomes for entrainment of anchovies using (a) the AEL model, (b) the FY model, or (c) the FH model when all parameters are uncertain and when a single parameter value is held fixed at its modal value. The curves depicted represent probability distributions that, for the sake of graphical comparisons, were rescaled such that the maxima of all curves are equal. The assumed variability of entrainment losses was set at +/-10% in the examples shown.**

**Table 13: Results of factor prioritization of the AEL model applied to entrainment losses (age 1 equivalents)**

<b>Species group</b>	<b>Model conditions</b>	<b>Point estimate (model outcome with mortality rates and entrainment fixed at modal values)</b>	<b>Coefficient of variation [(standard deviation among recalculated outcomes)/point estimate]</b>	<b>Reduction in variance (<math>V_i</math> %) of model outcome by fixing one parameter at the modal value</b>
Anchovies	Mortality rates and entrainment fixed	2.300E+06		
	All mortality rates variable; entrainment variable at +/-10%		0.734	
	Egg mortality rate fixed		0.732	< 0.1
	Larval mortality rate fixed		0.046	99.9
	Age 0+ mortality rate fixed		0.732	< 0.1
	Age 1 mortality rate fixed		0.729	< 0.1
	Age 2 mortality rate fixed		0.728	< 0.1
	Age 3 mortality rate fixed		0.72	< 0.1
	Entrainment fixed		0.731	< 0.1
Gobies	Mortality rates and entrainment fixed	3.777E+08		
	All mortality rates variable; entrainment variable at +/-10%		0.409	
	Egg mortality rate fixed		0.403	< 0.1
	Larval mortality rate fixed		0.158	26.4
	Age 0+ mortality rate fixed		0.363	26.4
	Age 1 mortality rate fixed		0.397	< 0.1
	Age 2 mortality rate fixed		0.401	< 0.1
	Age 3 mortality rate fixed		0.407	< 0.1
	Entrainment fixed		0.401	47.2
Blennies	Mortality rates and entrainment fixed	3.297E+08		
	All mortality rates variable; entrainment variable at +/-10%		0.327	
	Egg mortality rate fixed		0.335	< 0.1
	Larval mortality rate fixed		0.158	76.4
	Age 0+ mortality rate fixed		0.283	23.4
	Age 1 mortality rate fixed		0.331	< 0.1
	Age 2 mortality rate fixed		0.329	< 0.1
	Age 3 mortality rate fixed		0.331	< 0.1
	Entrainment fixed		0.325	0.2

**Table 13: Results of factor prioritization of the AEL model applied to entrainment losses (age 1 equivalents)**

<b>Species group</b>	<b>Model conditions</b>	<b>Point estimate (model outcome with mortality rates and entrainment fixed at modal values)</b>	<b>Coefficient of variation [(standard deviation among recalculated outcomes)/point estimate]</b>	<b>Reduction in variance (<math>V_i</math> %) of model outcome by fixing one parameter at the modal value</b>
Rockfishes	Mortality rates and entrainment fixed	2.137E+07		
	All mortality rates variable; entrainment variable at +/-10%		1.023	
	Egg mortality rate fixed		1.034	< 0.1
	Larval mortality rate fixed		1.032	0.4
	Age 0+ mortality rate fixed		0.041	98.7
	Age 1 mortality rate fixed		1.03	< 0.1
	Age 2 mortality rate fixed		1.021	< 0.1
	Age 3 mortality rate fixed		1.039	< 0.1
	E Rates fixed		1.025	0.8
California halibut	Mortality rates and entrainment fixed	1.595E+06		
	All mortality rates variable; entrainment variable at +/-10%		0.477	
	Egg mortality rate fixed		0.478	< 0.1
	Larval mortality rate fixed		0.041	79.7
	Age 0+ mortality rate fixed		0.477	9.7
	Age 1 mortality rate fixed		0.479	< 0.1
	Age 2 mortality rate fixed		0.476	< 0.1
	Age 3 mortality rate fixed		0.473	< 0.1
	Entrainment fixed		0.478	10.6
Crabs	Mortality rates and entrainment fixed	4.430E+05		
	All mortality rates variable; entrainment variable at +/-10%		2.033	
	Egg mortality rate fixed		2.0	< 0.1
	Larval mortality rate fixed		0.041	99.9
	Age 0+ mortality rate fixed		2.003	< 0.1
	Age 1 mortality rate fixed		2.009	< 0.1
	Age 2 mortality rate fixed		2.025	< 0.1
	Age 3 mortality rate fixed		1.982	< 0.1
	Entrainment fixed		2	< 0.1

For impingement, the parameter most influential to total uncertainty was mortality rate of the age  $\geq 1$  stage for blennies, rockfishes, surfperches, and California halibut (Table 14). The importance of age  $\geq 1$  mortality rates to impingement rates is partially because mortality rates of organisms age 1-age 4 are relevant for the translating losses of older fish into age one equivalents. Uncertainty associated with impingement rates was the greatest source of uncertainty for crabs. For all species except surfperch, uncertainty about mortality rates was secondary to uncertainty about loss rates, when those rates were set at +/-10 percent.

**Table 14: Results of factor prioritization of the AEL model applied to impingement losses (age 1 equivalents)**

<b>Species group</b>	<b>Model conditions</b>	<b>Point estimate (model outcome with mortality rates and entrainment fixed at modal values)</b>	<b>Coefficient of variation [(standard deviation among recalculated outcomes)/point estimate]</b>	<b>Reduction in variance (<math>V_i</math> %) of model outcome by fixing one parameter at the modal value</b>
Anchovies	Mortality rates and Impingement fixed	1.414E+07		
	All mortality rates variable; impingement variable at +/-10%		0.047	
	Egg mortality rate fixed		0.047	< 0.1
	Larval mortality rate fixed		0.048	< 0.1
	Age 0+ mortality rate fixed		0.047	< 0.1
	Age 1 mortality rate fixed		0.043	13.1
	Age 2 mortality rate fixed		0.046	11.5
	Age 3 mortality rate fixed		0.047	39.8
	Impingement fixed		0.024	35.7
Gobies	Mortality rates and Impingement fixed	2.060E+05		
	All mortality rates variable; impingement variable at +/-10%		0.043	
	Egg mortality rate fixed		0.043	< 0.1
	Larval mortality rate fixed		0.044	< 0.1
	Age 0+ mortality rate fixed		0.043	< 0.1
	Age 1 mortality rate fixed		0.041	13.7
	Age 2 mortality rate fixed		0.044	10.4
	Age 3 mortality rate fixed		0.044	46.5
	Impingement fixed		0.015	29.4
Blennies	Mortality rates and Impingement fixed	3.287E+03		
	All mortality rates variable; impingement variable at +/-10%		0.068	
	Egg mortality rate fixed		0.069	< 0.1
	Larval mortality rate fixed		0.069	< 0.1
	Age 0+ mortality rate fixed		0.068	< 0.1
	Age 1 mortality rate fixed		0.045	27.1
	Age 2 mortality rate fixed		0.067	6.8
	Age 3 mortality rate fixed		0.068	28.2
	Impingement fixed		0.056	37.8

**Table 14: Results of factor prioritization of the AEL model applied to impingement losses (age 1 equivalents)**

<b>Species group</b>	<b>Model conditions</b>	<b>Point estimate (model outcome with mortality rates and entrainment fixed at modal values)</b>	<b>Coefficient of variation [(standard deviation among recalculated outcomes)/point estimate]</b>	<b>Reduction in variance (<math>V_i</math> %) of model outcome by fixing one parameter at the modal value</b>
Rockfishes	Mortality rates and Impingement fixed	7.381E+05		
	All mortality rates variable; impingement variable at +/-10%		0.224	
	Egg mortality rate fixed		0.224	< 0.1
	Larval mortality rate fixed		0.223	< 0.1
	Age 0+ mortality rate fixed		0.227	< 0.1
	Age 1 mortality rate fixed		0.044	6.1
	Age 2 mortality rate fixed		0.226	12.7
	Age 3 mortality rate fixed		0.225	49.0
	Impingement fixed		0.223	32.1
Surfperches	Mortality rates and Impingement fixed	2.133E+06		
	All mortality rates variable; impingement variable at +/-10%		0.149	
	Egg mortality rate fixed		0.147	< 0.1
	Larval mortality rate fixed		0.149	< 0.1
	Age 0+ mortality rate fixed		0.147	< 0.1
	Age 1 mortality rate fixed		0.045	6.0
	Age 2 mortality rate fixed		0.148	12.3
	Age 3 mortality rate fixed		0.148	48.4
	Impingement fixed		0.143	33.2
California halibut	Mortality rates and entrainment fixed	4.340E+03		
	All mortality rates variable; impingement variable at +/-10%		0.071	
	Egg mortality rate fixed		0.07	< 0.1
	Larval mortality rate fixed		0.071	< 0.1
	Age 0+ mortality rate fixed		0.071	< 0.1
	Age 1 mortality rate fixed		0.05	20.6
	Age 2 mortality rate fixed		0.067	13.1
	Age 3 mortality rate fixed		0.069	35.5
	Impingement fixed		0.057	30.8
Crabs	Mortality rates and	1.120E+06		

**Table 14: Results of factor prioritization of the AEL model applied to impingement losses (age 1 equivalents)**

Species group	Model conditions	Point estimate (model outcome with mortality rates and entrainment fixed at modal values)	Coefficient of variation [(standard deviation among recalculated outcomes)/point estimate]	Reduction in variance ( $V_i$ %) of model outcome by fixing one parameter at the modal value
	impingement fixed			
	All mortality rates variable; impingement variable at +/-10%		0.041	
	Egg mortality rate fixed		0.041	< 0.1
	Larval mortality rate fixed		0.04	< 0.1
	Age 0+ mortality rate fixed		0.04	< 0.1
	Age 1 mortality rate fixed		0.041	4.4
	Age 2 mortality rate fixed		0.041	4.4
	Age 3 mortality rate fixed		0.041	17.7
	Impingement fixed		0	73.4

### 3.2.2 FY Model

#### 3.2.2.1 Total Uncertainty

The FY model was assessed for anchovies, rockfishes, California halibut, surfperches (entrainment only) and crabs. The FY model was not assessed for gobies or blennies because they are not harvested.

The FY model was less precise than the AEL model. The total CV of the FY model applied to entrainment losses (Table 15) ranged from 0.549 (for California halibut) to 6.65 (for crabs). The general magnitude of uncertainty in the outcome the FY model for entrainment losses was notably large, especially for crabs where the CV exceeded 6.65 (665 percent) and for rockfishes where the CV was almost 3 (300 percent).

**Table 15: Results of factor prioritization of the FY model applied to entrainment losses (forgone yield; kg)**

<b>Species group</b>	<b>Model conditions</b>	<b>Point estimate (model outcome with mortality rates and entrainment fixed at modal values)</b>	<b>Coefficient of variation [(standard deviation among recalculated outcomes)/point estimate]</b>	<b>Reduction in variance (<math>V_i</math> %) of model outcome by fixing one parameter at the modal value</b>
Anchovies	Mortality rates and entrainment fixed	8.817E+03		
	All mortality rates variable; entrainment variable at +/-10%		0.75	
	Egg mortality rate fixed		0.75	2.8
	Larval mortality rate fixed		0.119	< 0.1
	Age 0+ mortality rate fixed		0.748	< 0.1
	Age 1 mortality rate fixed		0.736	17.3
	Age 2 mortality rate fixed		0.736	15.8
	Age 3 mortality rate fixed		0.738	30.9
	Entrainment fixed		0.746	33.2
Rockfishes	Mortality rates and entrainment fixed	9.364E+04		
	All mortality rates variable; entrainment variable at +/-10%		2.973	
	Egg mortality rate fixed		2.952	< 0.1
	Larval mortality rate fixed		3.043	13.9
	Age 0+ mortality rate fixed		1.584	3.7
	Age 1 mortality rate fixed		1.103	13.9
	Age 2 mortality rate fixed		3.039	3.0
	Age 3 mortality rate fixed		2.947	38.2
	Entrainment fixed		3.121	27.3
California halibut	Mortality rates and entrainment fixed	3.079E+05		
	All mortality rates variable; entrainment variable at +/-10%		0.549	
	Egg mortality rate fixed		0.54	< 0.1
	Larval mortality rate fixed		0.218	21.6
	Age 0+ mortality rate fixed		0.54	< 0.1
	Age 1 mortality rate fixed		0.544	< 0.1
	Age 2 mortality rate fixed		0.537	< 0.1
	Age 3 mortality rate fixed		0.536	47.3
	Entrainment fixed		0.547	31.2

**Table 15: Results of factor prioritization of the FY model applied to entrainment losses (forgone yield; kg)**

<b>Species group</b>	<b>Model conditions</b>	<b>Point estimate (model outcome with mortality rates and entrainment fixed at modal values)</b>	<b>Coefficient of variation [(standard deviation among recalculated outcomes)/point estimate]</b>	<b>Reduction in variance (<math>V_i</math> %) of model outcome by fixing one parameter at the modal value</b>
Crabs	Mortality rates and entrainment fixed	9.337		
	All mortality rates variable; entrainment variable at +/-10%		6.65	
	Egg mortality rate fixed		6.938	< 0.1
	Larval mortality rate fixed		2.025	< 0.1
	Age 0+ mortality rate fixed		6.28	< 0.1
	Age 1 mortality rate fixed		2.031	32.6
	Age 2 mortality rate fixed		6.373	14.9
	Age 3 mortality rate fixed		6.042	25.8
	Entrainment fixed		6.628	26.7

For impingement losses (Table 16) CVs ranged from 0.13 (for anchovies) to 2.05 (for crabs). The overall ranking of species groups from greatest precision to least precision was anchovies > surfperches > California halibut > rockfishes > crabs.

**Table 16: Results of factor prioritization of the FY model applied to impingement losses (forgone yield; kg)**

<b>Species group</b>	<b>Model conditions</b>	<b>Point estimate (model outcome with mortality rates and entrainment fixed at modal values)</b>	<b>Coefficient of variation [(standard deviation among recalculated outcomes)/point estimate]</b>	<b>Reduction in variance (<math>V_i</math> %) of model outcome by fixing one parameter at the modal value</b>
Anchovies	Mortality rates and Impingement fixed	5.421E+04		
	All mortality rates variable; impingement variable at +/-10%		0.13	
	Egg mortality rate fixed		0.129	< 0.1
	Larval mortality rate fixed		0.131	< 0.1
	Age 0+ mortality rate fixed		0.129	< 0.1
	Age 1 mortality rate fixed		0.079	10.8
	Age 2 mortality rate fixed		0.114	10.6
	Age 3 mortality rate fixed		0.128	45.3
	Impingement fixed		0.122	33.3
Rockfishes	Mortality rates and impingement fixed	3.234E+03		
	All mortality rates variable; impingement variable at +/-10%		0.69	
	Egg mortality rate fixed		0.69	< 0.1
	Larval mortality rate fixed		0.682	< 0.1
	Age 0+ mortality rate fixed		0.696	< 0.1
	Age 1 mortality rate fixed		0.208	54.4
	Age 2 mortality rate fixed		0.671	4.6
	Age 3 mortality rate fixed		0.67	23.9
	Impingement fixed		0.686	17.1
Surfperches	Mortality rates and impingement fixed	1.192E+04		
	All mortality rates variable; impingement variable at +/-10%		0.179	
	Egg mortality rate fixed		0.179	< 0.1
	Larval mortality rate fixed		0.179	< 0.1
	Age 0+ mortality rate fixed		0.178	< 0.1
	Age 1 mortality rate fixed		0.138	31.1
	Age 2 mortality rate fixed		0.15	7.1
	Age 3 mortality rate fixed		0.162	35.9
	Impingement fixed		0.174	25.9

**Table 16: Results of factor prioritization of the FY model applied to impingement losses (forgone yield; kg)**

<b>Species group</b>	<b>Model conditions</b>	<b>Point estimate (model outcome with mortality rates and entrainment fixed at modal values)</b>	<b>Coefficient of variation [(standard deviation among recalculated outcomes)/point estimate]</b>	<b>Reduction in variance (V<sub>i</sub> %) of model outcome by fixing one parameter at the modal value</b>
California halibut	Mortality rates and impingement fixed	8.379E+02		
	All mortality rates variable; impingement variable at +/-10%		0.209	
	Egg mortality rate fixed		0.208	< 0.1
	Larval mortality rate fixed		0.206	< 0.1
	Age 0+ mortality rate fixed		0.204	< 0.1
	Age 1 mortality rate fixed		0.208	11.1
	Age 2 mortality rate fixed		0.207	11.1
	Age 3 mortality rate fixed		0.205	55.7
	Impingement fixed		0.202	22.1
Crabs	Mortality rates and Impingement fixed	2.360E+01		
	All mortality rates variable; impingement variable at +/-10%		2.053	
	Egg mortality rate fixed		2.034	< 0.1
	Larval mortality rate fixed		2.03	< 0.1
	Age 0+ mortality rate fixed		2.048	< 0.1
	Age 1 mortality rate fixed		0.047	79.9
	Age 2 mortality rate fixed		2.021	1.6
	Age 3 mortality rate fixed		2.059	10.8
	Impingement fixed		2.039	7.6

### 3.2.2.2 Factor Prioritization

For both entrainment and impingement, the parameters most influential to total uncertainty were mortality rates of age classes vulnerable to fishing mortality (Table 15). In all cases, uncertainty in entrainment or impingement loss rates were also important contributors to total uncertainty, though clearly secondary to uncertainty in mortality rates. For entrainment losses of California halibut and rockfishes, mortality rate of the youngest life stage (larvae and age 0+ , respectively) was also influential.

### 3.2.3 FH Model

#### 3.2.3.1 *Total Uncertainty*

Uncertainty associated with the FH model was smaller than the FY model and similar to that of the AEL approach, although species differences were observed. The CV of the FH model applied to entrainment losses (Table 17) ranged from 0.134 (for gobies) to 1.75 (for blennies). For entrainment the overall ranking of species groups from greatest precision to least precision was gobies > rockfishes > California halibut > anchovies > crabs > blennies.

The CV of the FH model applied to impingement losses (Table 18) was somewhat greater ranging from 0.477 (for gobies) to 3.34 (for crabs). The general magnitude of uncertainty in the FH model applied to impingement losses was notably large for crabs where the CV exceeded 3.33 (333 percent) and for blennies where the CV exceeded 2 (200 percent). For impingement the overall ranking of species groups from greatest precision to least precision was gobies > surfperches > California halibut > anchovies > rockfishes > blennies > crabs.

**Table 17: Results of factor prioritization of the FH model applied to entrainment losses (equivalent spawners)**

<b>Species group</b>	<b>Model conditions</b>	<b>Point estimate (model outcome with mortality rates and entrainment fixed at modal values)</b>	<b>Coefficient of variation [(standard deviation among recalculated outcomes)/point estimate]</b>	<b>Reduction in variance (<math>V_i</math> %) of model outcome by fixing one parameter at the modal value</b>
Anchovies	Mortality rates and entrainment fixed	2.901E+05		
	All mortality rates variable; fecundity rate variable; entrainment variable at +/-10%		0.482	
	Egg mortality rate fixed		0.474	14.7
	Larval mortality rate fixed		0.486	14.2
	Age 0+ mortality rate fixed		0.476	< 0.1
	Age 1 mortality rate fixed		0.48	< 0.1
	Age 2 mortality rate fixed		0.479	< 0.1
	Age 3 mortality rate fixed		0.493	< 0.1
	Entrainment fixed		0.492	15.1
Lifetime Fecundity fixed		0.065	56.0	
Gobies	Mortality rates and entrainment fixed	2.823E+07		
	All mortality rates variable; fecundity rate variable; entrainment variable at +/-10%		0.134	
	Egg mortality rate fixed		0.132	39.7
	Larval mortality rate fixed		0.129	21.7
	Age 0+ mortality rate fixed		0.137	< 0.1
	Age 1 mortality rate fixed		0.134	< 0.1
	Age 2 mortality rate fixed		0.134	< 0.1
	Age 3 mortality rate fixed		0.135	< 0.1
	Entrainment fixed		0.129	38.5
Lifetime Fecundity fixed		0.058	< 0.1	

**Table 17: Results of factor prioritization of the FH model applied to entrainment losses (equivalent spawners)**

<b>Species group</b>	<b>Model conditions</b>	<b>Point estimate (model outcome with mortality rates and entrainment fixed at modal values)</b>	<b>Coefficient of variation [(standard deviation among recalculated outcomes)/point estimate]</b>	<b>Reduction in variance (<math>V_i</math> %) of model outcome by fixing one parameter at the modal value</b>
Blennies	Mortality rates and entrainment fixed	1.041E+05		
	All mortality rates variable; fecundity rate variable; entrainment variable at +/-10%		1.747	
	Egg mortality rate fixed		2.296	< 0.1
	Larval mortality rate fixed		1.734	3.6
	Age 0+ mortality rate fixed		2.376	< 0.1
	Age 1 mortality rate fixed		5.735	< 0.1
	Age 2 mortality rate fixed		1.854	< 0.1
	Age 3 mortality rate fixed		2.041	< 0.1
	Entrainment fixed		2.282	< 0.1
	Lifetime Fecundity fixed		0.049	96.4
Rockfishes	Mortality rates and entrainment fixed	2.719E+03		
	All mortality rates variable; fecundity rate variable; entrainment variable at +/-10%		0.244	
	Egg mortality rate fixed		0.245	0.8
	Larval mortality rate fixed		0.245	0.8
	Age 0+ mortality rate fixed		0.244	88.4
	Age 1 mortality rate fixed		0.246	< 0.1
	Age 2 mortality rate fixed		0.245	< 0.1
	Age 3 mortality rate fixed		0.243	< 0.1
	Entrainment fixed		0.244	1.6
	Lifetime Fecundity fixed		0.058	8.2

**Table 17: Results of factor prioritization of the FH model applied to entrainment losses (equivalent spawners)**

<b>Species group</b>	<b>Model conditions</b>	<b>Point estimate (model outcome with mortality rates and entrainment fixed at modal values)</b>	<b>Coefficient of variation [(standard deviation among recalculated outcomes)/point estimate]</b>	<b>Reduction in variance (<math>V_i</math> %) of model outcome by fixing one parameter at the modal value</b>
California halibut	Mortality rates and entrainment fixed	3.692E+00		
	All mortality rates variable; fecundity rate variable; entrainment variable at +/-10%		0.384	
	Egg mortality rate fixed		0.375	4.6
	Larval mortality rate fixed		0.382	55.0
	Age 0+ mortality rate fixed		0.375	< 0.1
	Age 1 mortality rate fixed		0.381	< 0.1
	Age 2 mortality rate fixed		0.384	< 0.1
	Age 3 mortality rate fixed		0.381	< 0.1
	Entrainment fixed		0.371	4.8
Lifetime Fecundity fixed		0.076	35.6	
Crabs	Mortality rates and entrainment fixed	9.597E+04		
	All mortality rates variable; fecundity rate variable; entrainment variable at +/-10%		0.749	
	Egg mortality rate fixed		0.692	4.6
	Larval mortality rate fixed		0.756	72.3
	Age 0+ mortality rate fixed		0.752	< 0.1
	Age 1 mortality rate fixed		0.741	< 0.1
	Age 2 mortality rate fixed		0.771	< 0.1
	Age 3 mortality rate fixed		0.775	< 0.1
	Entrainment fixed		0.74	3.5
Lifetime Fecundity fixed		0.165	19.4	

**Table 18: Results of factor prioritization of the FH model applied to impingement losses (equivalent spawners)**

<b>Species group</b>	<b>Model conditions</b>	<b>Point estimate (model outcome with mortality rates and entrainment fixed at modal values)</b>	<b>Coefficient of variation [(standard deviation among recalculated outcomes)/point estimate]</b>	<b>Reduction in variance (<math>V_i</math> %) of model outcome by fixing one parameter at the modal value</b>
Anchovies	Mortality rates and Impingement fixed	1.784E+06		
	All mortality rates variable; fecundity rate variable; impingement variable at +/-10%		1.087	
	Egg mortality rate fixed		1.092	4.7
	Larval mortality rate fixed		0.489	55.3
	Age 0+ mortality rate fixed		1.068	4.5
	Age 1 mortality rate fixed		1.08	4.5
	Age 2 mortality rate fixed		1.088	< 0.1
	Age 3 mortality rate fixed		1.127	< 0.1
	Impingement fixed		1.13	9.1
	Lifetime Fecundity fixed		0.735	21.7
Gobies	Mortality rates and Impingement fixed	1.540E+04		
	All mortality rates variable; fecundity rate variable; impingement variable at +/-10%		0.477	
	Egg mortality rate fixed		0.475	19.8
	Larval mortality rate fixed		0.204	10.4
	Age 0+ mortality rate fixed		0.442	10.4
	Age 1 mortality rate fixed		0.476	20.2
	Age 2 mortality rate fixed		0.473	< 0.1
	Age 3 mortality rate fixed		0.472	< 0.1
	Impingement fixed		0.471	39.3
Lifetime Fecundity fixed		0.452	< 0.1	

**Table 18: Results of factor prioritization of the FH model applied to impingement losses (equivalent spawners)**

<b>Species group</b>	<b>Model conditions</b>	<b>Point estimate (model outcome with mortality rates and entrainment fixed at modal values)</b>	<b>Coefficient of variation [(standard deviation among recalculated outcomes)/point estimate]</b>	<b>Reduction in variance (<math>V_i</math> %) of model outcome by fixing one parameter at the modal value</b>
Blennies	Mortality rates and Impingement fixed	1.038E+00		
	All mortality rates variable; fecundity rate variable; impingement variable at +/-10%		2.05	
	Egg mortality rate fixed		2.473	< 0.1
	Larval mortality rate fixed		1.663	4.6
	Age 0+ mortality rate fixed		2.543	< 0.1
	Age 1 mortality rate fixed		5.775	< 0.1
	Age 2 mortality rate fixed		2.202	< 0.1
	Age 3 mortality rate fixed		2.254	< 0.1
	Impingement fixed		2.588	< 0.1
	Lifetime Fecundity fixed		0.361	95.3
Rockfishes	Mortality rates and entrainment fixed	9.392E+01		
	All mortality rates variable; fecundity rate variable; impingement variable at +/-10%		1.347	
	Egg mortality rate fixed		1.336	3.5
	Larval mortality rate fixed		1.362	3.5
	Age 0+ mortality rate fixed		0.335	55.3
	Age 1 mortality rate fixed		1.349	24.1
	Age 2 mortality rate fixed		1.349	< 0.1
	Age 3 mortality rate fixed		1.319	< 0.1
	Impingement fixed		1.36	7.4
	Lifetime Fecundity fixed		1.163	5.9

**Table 18: Results of factor prioritization of the FH model applied to impingement losses (equivalent spawners)**

<b>Species group</b>	<b>Model conditions</b>	<b>Point estimate (model outcome with mortality rates and entrainment fixed at modal values)</b>	<b>Coefficient of variation [(standard deviation among recalculated outcomes)/point estimate]</b>	<b>Reduction in variance (<math>V_i</math> %) of model outcome by fixing one parameter at the modal value</b>
Surfperches	Mortality rates and entrainment fixed	5.115E+05		
	All mortality rates variable; fecundity rate variable; impingement variable at +/-10%		0.506	
	Egg mortality rate fixed		0.511	< 0.1
	Larval mortality rate fixed		0.512	< 0.1
	Age 0+ mortality rate fixed		0.395	39.2
	Age 1 mortality rate fixed		0.497	4.6
	Age 2 mortality rate fixed		0.506	< 0.1
	Age 3 mortality rate fixed		0.526	< 0.1
	Impingement fixed		0.5	0.4
	Lifetime Fecundity fixed		0.316	55.7
California halibut	Mortality rates and Impingement fixed	1.000E-02		
	All mortality rates variable; fecundity rate variable; impingement variable at +/-10%		0.788	
	Egg mortality rate fixed		0.789	4.2
	Larval mortality rate fixed		0.391	52.8
	Age 0+ mortality rate fixed		0.776	3.8
	Age 1 mortality rate fixed		0.783	3.9
	Age 2 mortality rate fixed		0.808	< 0.1
	Age 3 mortality rate fixed		0.784	< 0.1
	Impingement fixed		0.781	8.0
	Lifetime Fecundity fixed		0.559	27.1

**Table 18: Results of factor prioritization of the FH model applied to impingement losses (equivalent spawners)**

Species group	Model conditions	Point estimate (model outcome with mortality rates and entrainment fixed at modal values)	Coefficient of variation [(standard deviation among recalculated outcomes)/point estimate]	Reduction in variance ( $V_i$ %) of model outcome by fixing one parameter at the modal value
Crabs	Mortality rates and entrainment fixed	2.426E+05		
	All mortality rates variable; fecundity rate variable; impingement variable at +/-10%		3.335	
	Egg mortality rate fixed		3.039	< 0.1
	Larval mortality rate fixed		0.759	47.9
	Age 0+ mortality rate fixed		3.225	< 0.1
	Age 1 mortality rate fixed		3.367	45.2
	Age 2 mortality rate fixed		3.009	< 0.1
	Age 3 mortality rate fixed		3.249	< 0.1
	Impingement fixed		3.281	< 0.1
	Lifetime Fecundity fixed		2.088	6.8

### 3.2.3.2 Factor Prioritization

For entrainment of anchovies and blennies the parameter most influential to total uncertainty was lifetime fecundity, and larval mortality was most influential in the other species (Table 17).

For impingement, the parameter most influential to total uncertainty was lifetime fecundity for blennies and surfperches. For anchovies, gobies, and California halibut, the parameter most influential to total uncertainty was the mortality rate of larvae. For crabs, the mortality rates of larvae and age 1 were roughly equivalent. For rockfishes, the parameter most influential to total uncertainty was age 0+ mortality (Table 18). The finding that mortality rates of the youngest life stage was most influential differed from the prioritization for entrainment because most organisms killed by entrainment are larvae. For the FH model applied to larvae, the effect of variability in larval mortality rates enter the model only through the factor  $S^*_j$  (Equation 4), while for impingement losses larval mortality rates are directly relevant to the calculation of equivalent spawners.

### 3.2.4 Assessing the Effects of Uncertainty in Loss Rates

In the primary sensitivity analyses described above, the precision of entrainment or impingement loss rates was assumed to be +/-10 percent. Altering this assumption can affect the factor prioritization. We performed additional sensitivity analyses to evaluate the influence of varying loss rates. Specifically, we inspected estimates of CV while varying the loss rates

between +/-2 percent and +/-90 percent. We then assessed the effects of uncertainty in life history parameters relative to the uncertainty in empirical loss rates.

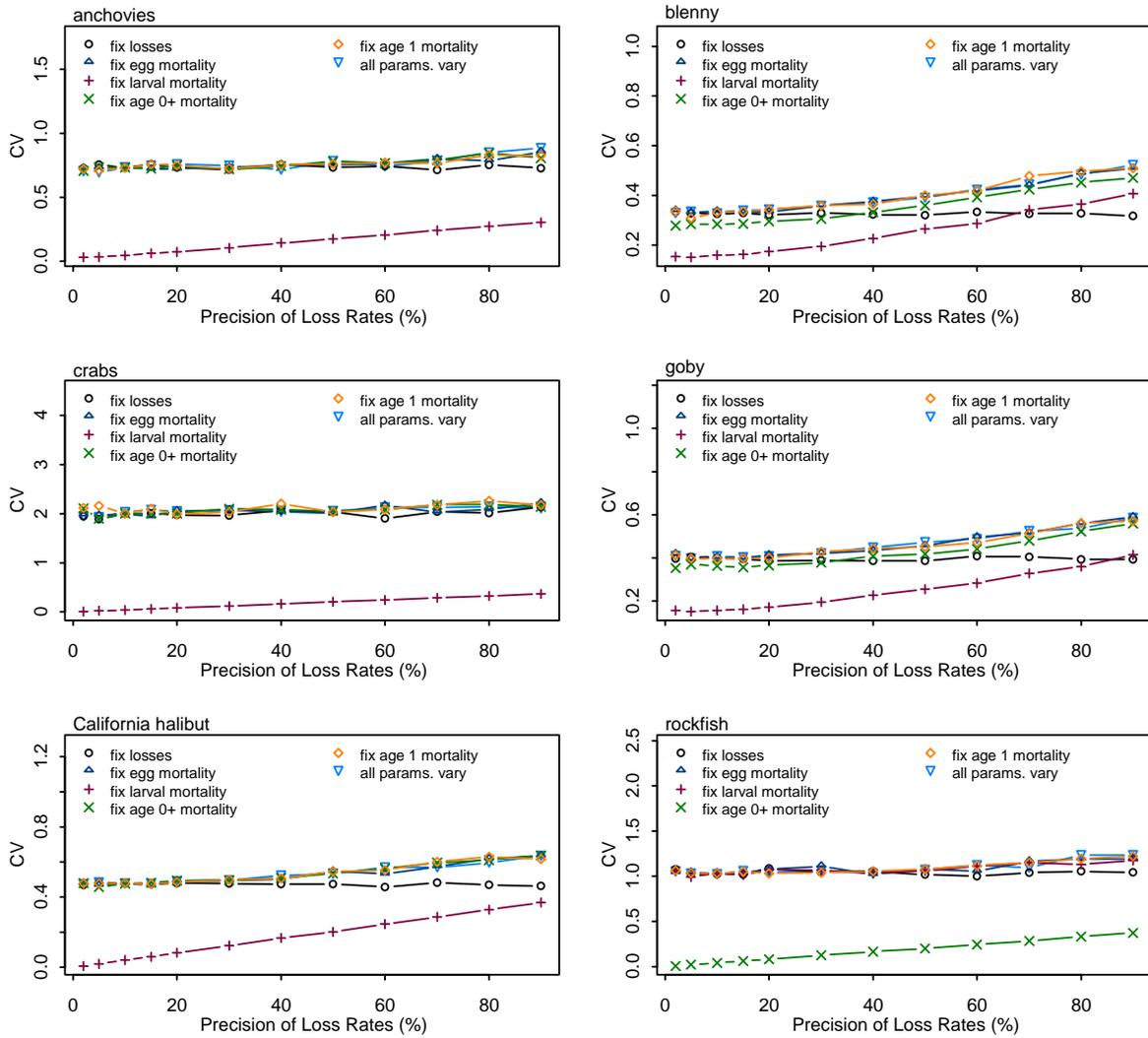
Graphical depictions of these series of analyses (Figures 2-7) illustrate the factor prioritization from the perspective of CV and, in some cases, demonstrate how the prioritization changes depending on the assumed precision of the empirical loss rates. Figures 2-7 display the same types of information reported in Tables 13-18 except the assumed precision of loss rates ranges from +/-2 percent to +/-90 percent instead of being fixed at +/-10 percent. In each of these plots, the line that is clearly below the majority of the lines indicates the CV of the model outcome when the value of the parameter contributing most to the total uncertainty is fixed at its modal value. The key feature in this series of plots are the points of intersection where the lines representing uncertainty in loss rates cross the lines representing other factors. The intersections, if present for a particular case, indicate scenarios where the imprecision in the estimated loss rates would be identified as the most important factor instead of another. Results of these analyses are reported in Section 3.2.5.

### 3.2.5 Summary of Sensitivity Analyses

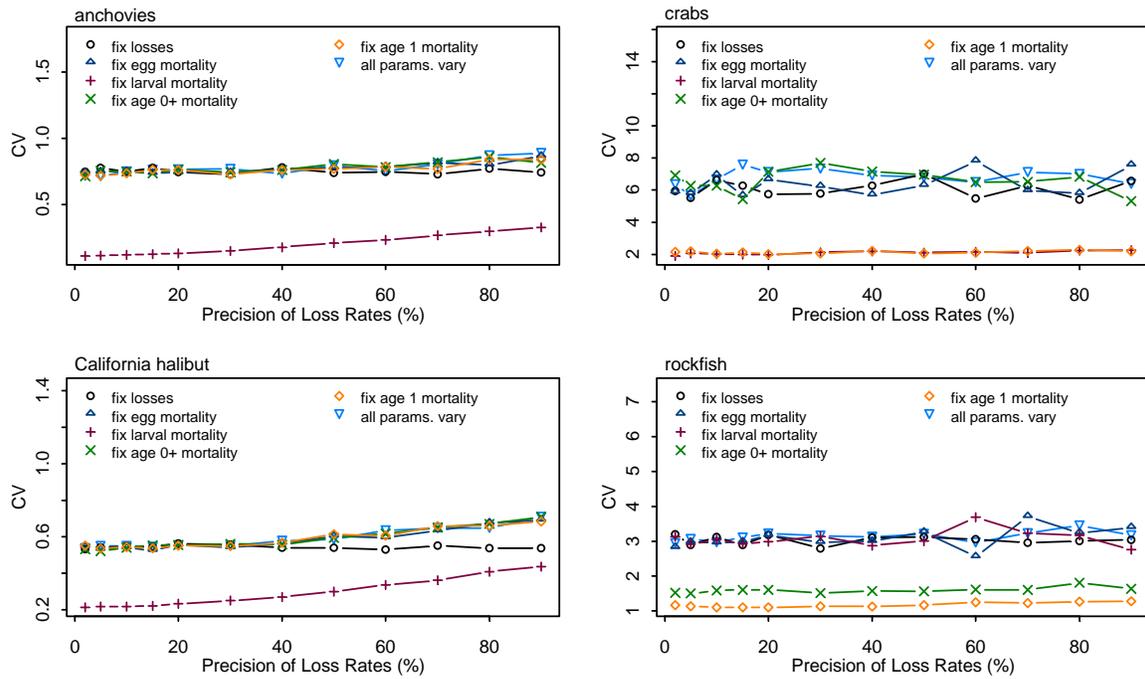
We assessed the relative precision of the metrics derived with each of the three models by inspecting the CV for each model application. We assessed the factor prioritization for each of the three models by ranking the values  $V_i$ , which quantified the fractional contribution of individual factors to the total uncertainty associated with an application of the model. Our primary analyses assumed entrainment and impingement loss rates were accurate to within +/-10 percent. A secondary series of analyses varied the assumed precision of the entrainment and impingement loss rates. Table 19 provides a summary of the key results of the study.

For entrainment, the precision of the FH models was better than either the AEL or the FY model for six of seven species groups (blennies were the exception). For these six species groups the ordering of the three models from most precise to least precise was  $FH > AEL > FY$ . The CV of the FH model applied to entrainment ranged from 0.13 to 0.75 for six species groups and was 1.75 for blennies. The large CV for blennies is driven by an exceptionally wide range of plausible fecundity values. For impingement, the relative precision of the three models differed; in all cases, the ordering of the three models from most precise to least precise was  $AEL > FY > FH$ . The CV of the AEL model for impingement losses was quite low, ranging from 0.04 to 0.22.

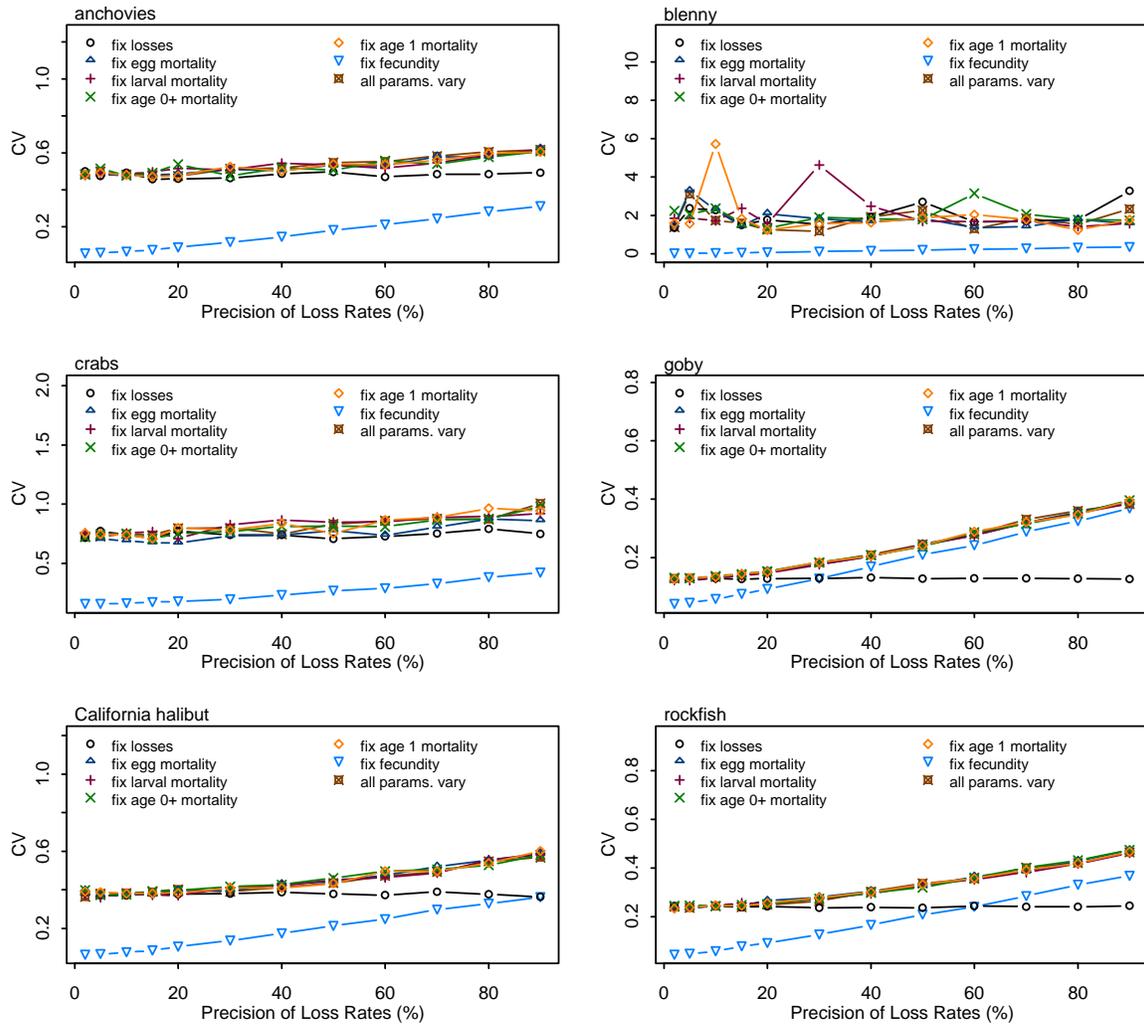
The factor prioritization of the AEL models for entrainment losses showed that uncertainty regarding larval mortality rates was the largest contributor to total uncertainty for anchovies, blennies, California halibut, and crabs (Table 13, Table 14). For rockfishes, the largest contributor to total uncertainty was uncertainty about mortality rates of the age 0+ stage, which is the youngest life stage for this viviparous species. The effect of fixing the most important ELS mortality rate for the AEL model is dramatic, as the value of the CV drops to nearly zero if the precision of loss rates is assumed to be good (e.g., less than 20 percent).



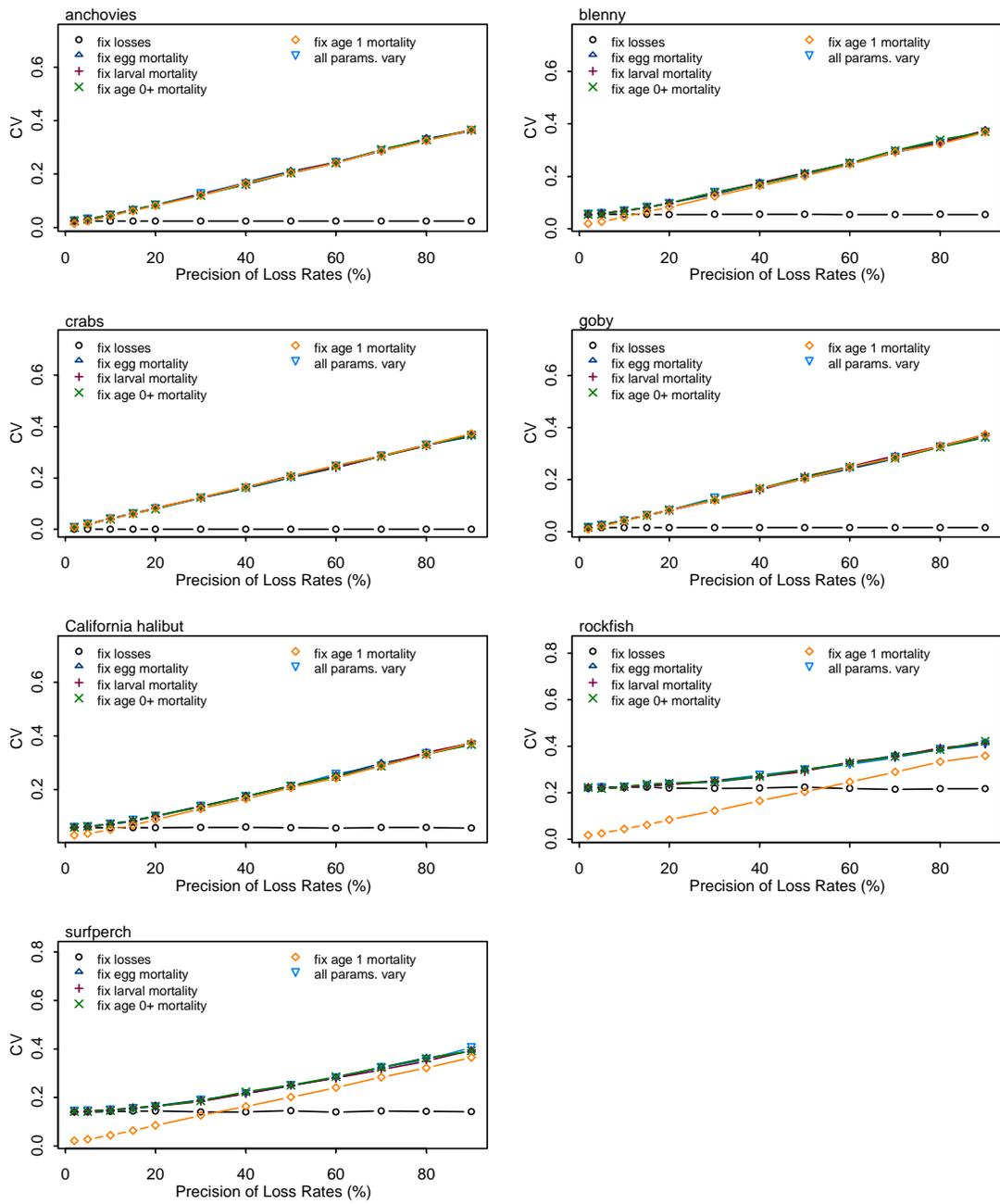
**Figure 2: Coefficient of variation (CV = SD/point estimate) in the age 1 equivalent model for entrainment losses, with assumed uncertainty in the precision of loss rates ranging from +/-2% +/-90%, evaluated with all parameters variable or with single parameters held fixed at a single (modal) value.**



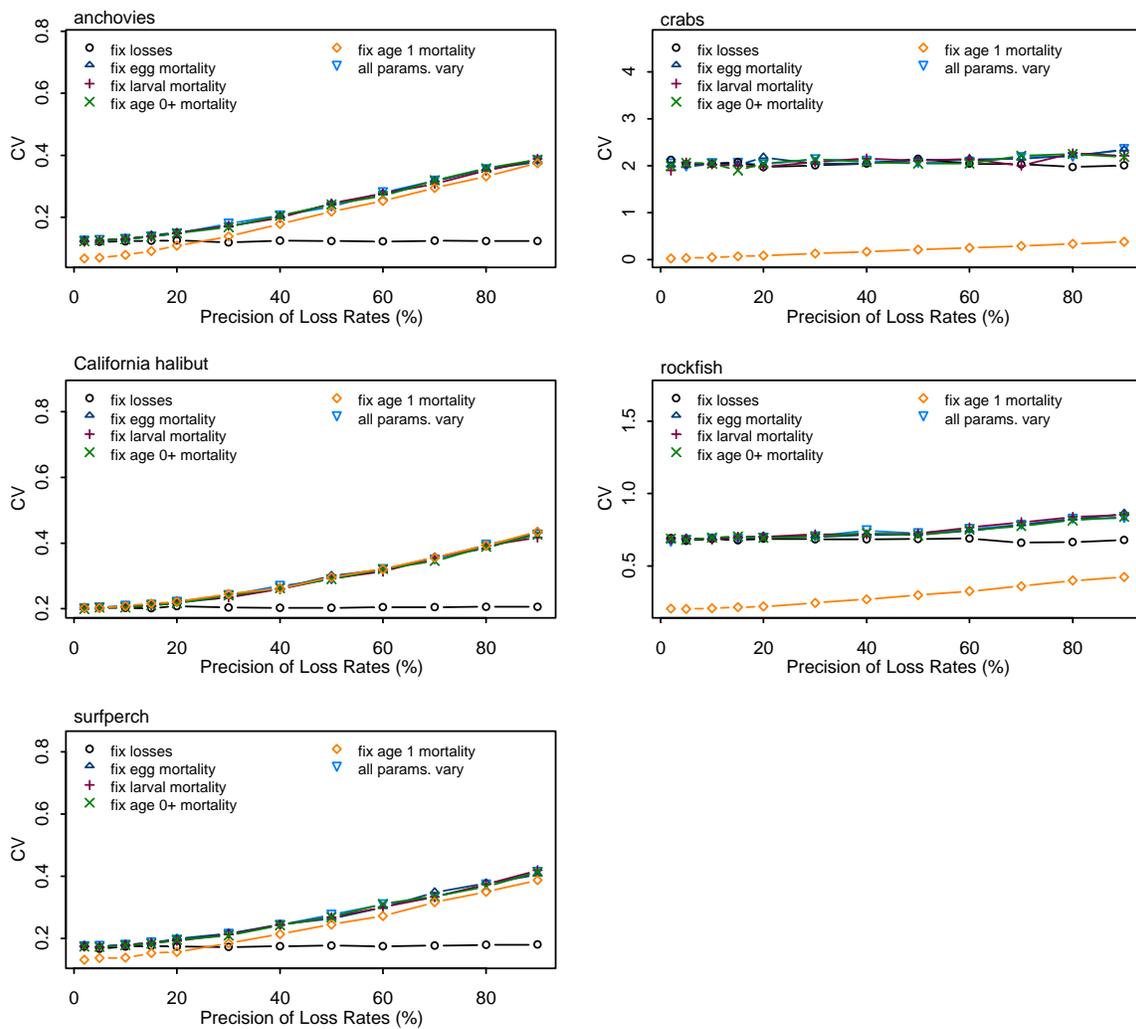
**Figure 3: Coefficient of variation (CV = SD/point estimate) in the forgone yield model for entrainment losses, with assumed uncertainty in the of entrainment loss rates ranging from +/-2%-+/-90%, evaluated with all parameters variable or with single parameters held fixed at a single (modal) value.**



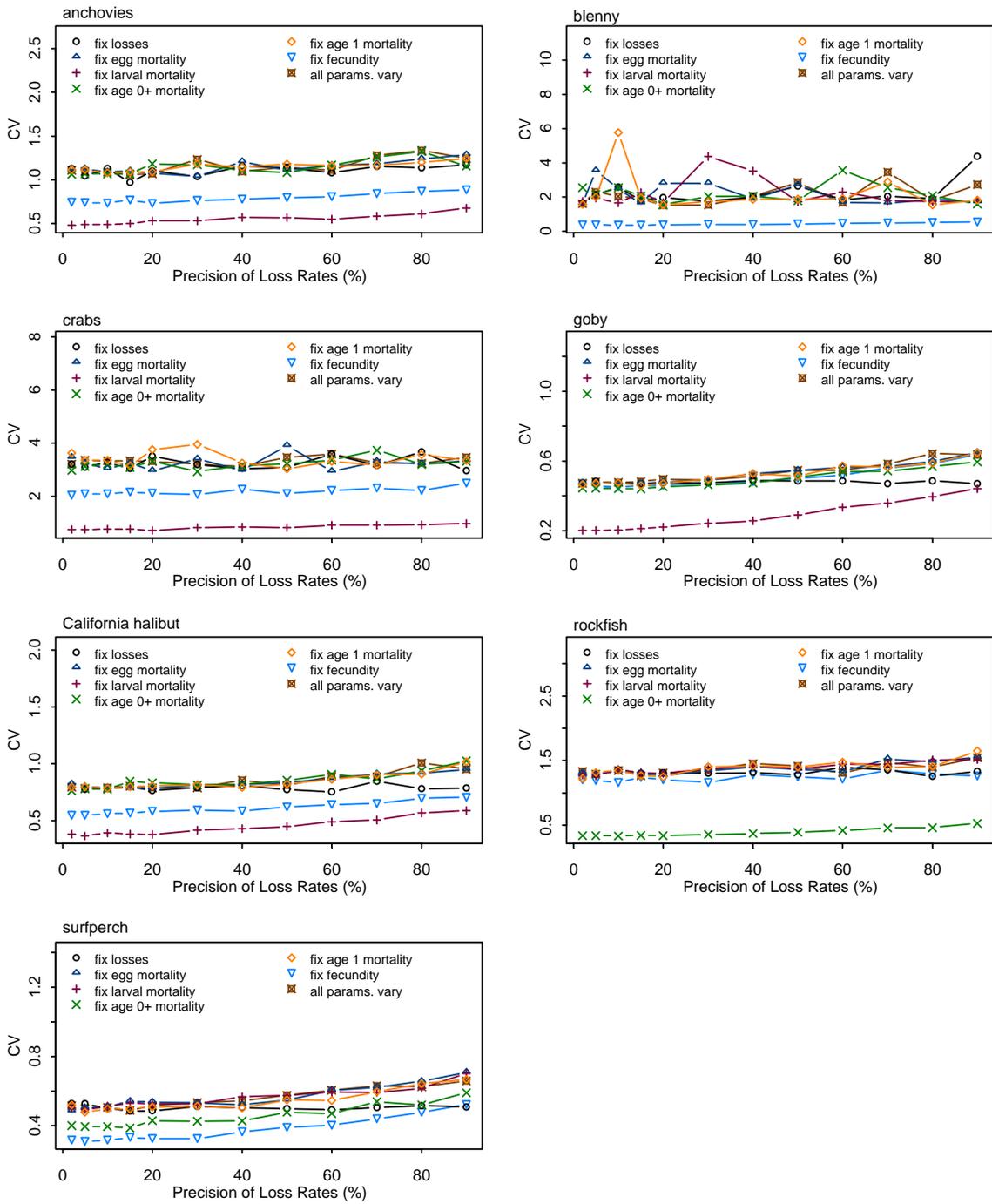
**Figure 4: Coefficient of variation (CV = SD/point estimate) in the fecundity hindcast model for entrainment losses, with assumed uncertainty in the precision of loss rates ranging from +/-2%-+/-90%, evaluated with all parameters variable or with single parameters held fixed at a single (modal) value.**



**Figure 5: Coefficient of variation (CV = SD/point estimate) in the age 1 equivalent model for impingement losses, with assumed uncertainty in the precision of loss rates ranging from +/-2%-+/-90%, evaluated with all parameters variable or with single parameters held fixed at a single (modal) value.**



**Figure 6: Coefficient of variation (CV = SD/point estimate) in the forgone yield model for impingement losses, with assumed uncertainty in the precision of loss rates ranging from +/-2%-+/-90%, evaluated with all parameters variable or with single parameters held fixed at a single (modal) value.**



**Figure 7: Coefficient of variation (CV = SD/point estimate) in the fecundity hindcast model for impingement losses, with assumed uncertainty in the precision of loss rates ranging from +/-2%-+/-90%, evaluated with all parameters variable or with single parameters held fixed at a single (modal) value.**

**Table 19: Summary of results of the sensitivity analyses evaluated with the assumed precision of loss rates set at +/-10%. Each cell reports the calculated coefficient of variation (expressed as a percentage), the most influential parameter contributing to total uncertainty (as determined by factor prioritization), and the threshold (if any) for the precision of loss rates where the contribution to total uncertainty related to loss rates exceeds the contribution of the indicated parameter.**

Loss mode	Model	Species						
		Anchovies	Gobies	Blennies	Rockfishes	Surfperches	California halibut	Crabs
Entrainment	AEL	73.4%	40.9%	32.7%	102%	NA	47.7%	203%
		Larval mortality	Larval mortality	Larval mortality	Age 0+ mortality	NA	Larval mortality	Larval mortality
		–	90%	70%	–	NA	–	–
	FY	75%	NA	NA	297%	NA	55%	665%
		Age ≥ 1 mortality	NA	NA	Age ≥ 1 mortality	NA	Age ≥ 1 mortality	Age ≥ 1 mortality
		–	NA	NA	–	NA	–	–
FH	48.2%	13.4%	175%	24.4%	NA	38.4%	74.9%	
	Fecundity	Egg mortality	Fecundity	Age 0+ mortality	NA	Larval mortality	Larval mortality	
	–	30%	–	60%	NA	90%	–	
Impingement	AEL	4.7%	4.3%	6.8%	22.4%	14.9%	7.1%	4.1%
		Age ≥ 1 mortality	Loss rate					
		5%	5%	15%	55%	35%	15%	–
	FY	13.0%	NA	NA	69.0%	17.9%	20.9%	205%
		Age ≥ 1 mortality	NA	NA	Age ≥ 1 mortality	Age ≥ 1 mortality	Age ≥ 1 mortality	Age ≥ 1 mortality
		25%	NA	NA	–	25%	–	–
FH	109%	47.7%	205%	135%	50.6%	78.8%	334%	
	Larval mortality	Loss rate	Fecundity	Age 0+ mortality	Fecundity	Larval mortality	Larval mortality	
	–	–	–	–	90%	–	–	

For the FY model applied to impingement or to entrainment, uncertainty in mortality rates of age classes vulnerable to fishing mortality were generally the largest contributors to total uncertainty.

For the FH model applied to entrainment (Table 17), uncertainty about lifetime fecundity was the most important factor for anchovies and blennies. In other species, uncertainty about mortality rates of the youngest age classes were the largest contributors to total uncertainty. The effect of fixing the fecundity parameter in the FH model varies by species but was especially dramatic for blennies, reducing the CV from about 174 percent to less than 5 percent.

With few exceptions, uncertainty about entrainment loss rates generally was not the largest contributor to total uncertainty for any of the models considered. For the AEL model applied to entrainment of blennies and gobies, uncertainty about loss rates was the largest contributor if uncertainty about entrainment exceeded +/-70 percent or +/-90 percent, respectively. For the FH model applied to entrainment of rockfishes, uncertainty about loss rates was the largest contributor only if uncertainty about entrainment exceeded +/-60 percent.

For the AEL model applied to impingement losses, the threshold of uncertainty about loss rates is about 5-15 percent for anchovies, blennies, gobies and California halibut. For these species, fixing the precision of the loss rates led to a dramatic reduction in CV. The threshold of uncertainty about loss rates was higher for rockfishes and surfperches (about 55 percent and 35 percent, respectively). For crabs, uncertainty in loss rates was a greater contributor than uncertainty about mortality rates at any age, and removing uncertainty in loss rates led to a dramatic reduction in CV. This result for crabs was unique in the study, and resulted in part from the relatively narrow range of mortality rates for crabs aged  $\geq 4$  years.

For the FY model applied to impingement losses, uncertainty about loss rates was the largest contributor to total uncertainty if uncertainty about loss rates was more than about 25-30 percent for anchovies or surfperches. For crabs and rockfishes, uncertainty about age 1 mortality was the greatest contributor to total uncertainty regardless of assumed precision of loss rates.

Uncertainty about larval mortality rates was the most important contributor to uncertainty in the FH model applied to impingement losses of anchovies, crabs, and California halibut. For rockfishes, the most important factor was age 0+ mortality. For blennies and surfperches, uncertainty about lifetime fecundity was the most important contributor to uncertainty in the FH model applied to impingement losses

# CHAPTER 4: Conclusions

## 4.1 Model Uncertainties

Our results indicate that interpretation of impingement and entrainment losses using any of the three demographic models evaluated should include consideration of uncertainty. Because of the different age distributions of fish subject to entrainment or impingement, the effects of uncertainty in parameter values translate into uncertainty about the model outputs differently for entrainment or impingement. For this reason, a model that provides the most precise metrics for assessing entrainment may not provide the most precise estimates for assessing impingement.

Improvement in model uncertainty will also depend on reducing the uncertainty in impingement and entrainment loss estimates. Our results suggest that it is important to ensure that these estimates are as precise as possible, preferably +/-10 percent or less.

### 4.1.1 Demographic Models Applied to Entrainment

For assessing entrainment losses, the ordering of the three models from most precise to least precise was FH > AEL > FY for five of the six species groups (blennies were the exception, where the AEL model was more precise than the FH model). Applications of the FY model to entrainment of crabs or rockfishes were especially imprecise. Our results suggest that the FH model may be the most reliable way to assess entrainment losses, particularly if uncertainty about lifetime fecundity can be reduced.

Outputs of the AEL model or the FY model applied to entrainment losses for selected California species can be made more precise by reducing uncertainty about mortality rates of early life stages. For the FY model, the best way to improve precision of model estimates would be to improve the precision of mortality rates among age classes vulnerable to fishing mortality. The AEL model and the FY applied to entrainment losses were sensitive to uncertainty about larval mortality rates in all species considered except for rockfishes, where uncertainty about age 0+ mortality rates was most influential. Uncertainty about ELS mortality rates appears to be particularly influential for interpreting entrainment losses of crabs, rockfishes, and anchovies with the AEL model.

### 4.1.2 Demographic Models Applied to Impingement

For assessing impingement losses, the relative precision of the three models was different than for entrainment. For each of the species groups subject to impingement, the ordering of the three models from most precise to least precise was AEL > FY > FH. Application of the FH model to impingement losses was much less precise than either of the other models. These results suggest that the AEL model may be the most reliable way to assess impingement losses.

Uncertainty in output values from the AEL model and the FY model applied to impingement losses for selected California species cannot be reduced by reducing uncertainty about ELS mortality rates because those rates are not pertinent for determining equivalency for the older

organisms killed by impingement. For the FY model, the best way to improve precision of model estimates would be to improve the precision of mortality rates among age classes vulnerable to fishing mortality. Uncertainty about outputs of the AEL for impinged fishes is driven mostly by uncertainty about age  $\geq 1$  mortality or uncertainty about impingement loss rates. In contrast, uncertainty about metrics derived with the FH model for impinged fishes is mainly influenced by uncertainty about ELS mortality rates.

## 4.2 Influence of life History Types

The species groups selected for these analyses vary widely with respect to life history and ecological characteristics. However, results of the analyses indicate that the properties of the FH model for assessing entrainment is largely consistent across species groups. For six of the seven species groups, the FH model has the smallest amount of uncertainty for assessing entrainment. Although blennies and gobies are similar in many life history characteristics, blennies are the only exception to this pattern because of exceptionally large uncertainty in lifetime fecundity of blennies. This distinction is probably not because of an essential difference between blennies and the other species groups, but is more likely the result of diversity among blenny species with respect to fecundity.

There is exceptionally large uncertainty in AEL and FY models for assessing entrainment of anchovies, crabs, and rockfishes. Although these results are directly linked to uncertainty in ELS mortality rates (larval stage for anchovies and crabs; age 0+ for rockfishes), the results are indirectly linked to the life history of these species because the large uncertainty arises in part from the complexity of interactions between ocean currents and dispersal of ELS organisms. For crabs and rockfish, the difficulties associated with sampling benthic organisms also hinder estimation of vital rates the early life stages. The large uncertainty in ELS crab mortality rates also stems from the complexity of the crab life cycle, which includes both planktonic stages and benthic stages, and significant migrations that are partially dependent on ocean currents. Similarly, sampling ELS rockfishes is complicated by the fact that they settle to the benthic zone.

Compared to entrainment, differences between the models for impingement are relatively minor. Despite the different ecological characteristics of these species groups, they all become vulnerable to impingement at some point in their life cycle. Other species may not be vulnerable to impingement because of differences in habitat usage or differences in their ability to avoid impingement.

## CHAPTER 5: Recommendations

In most contexts, the reliability of results of demographic models will be highly dependent on the validity of vital rates used as parameters in the models, so identification of appropriate values (and plausible ranges) for a particular application will be required.

Based on these findings, provided that sufficiently valid vital rates are available, we recommend that 316(b) studies quantify the precision of annual impingement and entrainment and fecundity and mortality rates in order to help analysts interpret metrics derived with AEL, FY, and FH models. Results of our sensitivity analyses, or new analyses using similar methods, can also help permitting agencies define acceptable levels of uncertainty in the impingement and entrainment estimates used to evaluate performance relative to performance-based standards. Reducing uncertainty in lifetime fecundity may be the best way to improve assessment of entrainment because of its influential role in the FH model. The costs involved in reducing uncertainty in lifetime fecundity are likely to be substantially less than the costs involved in acquiring better estimates of ELS mortality rates. The available literature indicates substantial uncertainty regarding larval mortality rates for most species, suggesting that it could prove difficult to improve larval mortality estimates, even with local studies.

Specific recommendations include:

- Use the FH model for assessing entrainment losses because estimation of equivalent spawners can be done with greater precision than estimation of age 1 equivalents or forgone yield.
- To improve the utility of the FH model applied to entrainment, focus additional field research on improving estimates of lifetime fecundity.
- Use the AEL model for assessing impingement losses because for older individuals estimation of age 1 equivalents can be done with greater precision than estimation of forgone yield or equivalent spawners.
- To improve the utility of the AEL model applied to impingement or entrainment, focus additional field research on early life stage survival rates.
- Use caution when applying any of the models to crabs because uncertainties about ELS mortality rates for this group are relatively large, particularly in comparison to fish species. Because entrainment losses of crab larvae can be very large, additional research should focus on mortality rates of ELS crab if uncertainty is to be reduced meaningfully.
- Improvement in model uncertainty will also depend on reducing the uncertainty in impingement and entrainment loss estimates, therefore strive to ensure that these estimates are as precise as possible (preferably +/-10 percent or less).

- In 316(b) studies, quantify the precision of annual impingement and entrainment and fecundity and mortality rates to help analysts interpret metrics derived with AEL, FY, and FH models.
- Consider developing performance objectives for the acceptable degree of uncertainty in 316(b) studies that rely on any of the alternative metrics of entrainment or impingement losses, including objectives for the degree of uncertainty about actual loss rates and uncertainty in estimates derived from demographic models.

## **CHAPTER 6: Benefits to California**

The results of this study can be used by regulators who must interpret the significance of impingement and entrainment losses. Use of demographic models makes it possible to standardize losses of multiple ages in terms of a common life stage and to put losses of eggs and larvae in context. However, our analysis makes it clear that there can be significant uncertainties in results of these models depending on the uncertainty in model inputs. The results of this study can help regulators interpret the significance of model estimates given these uncertainties.

Sensitivity analyses such as ours can also help regulators define acceptable levels of uncertainty in the estimates used by facilities to evaluate performance relative to performance-based standards. For example, our analysis showed that for the AEL model applied to impingement losses, the threshold of uncertainty about loss rates is about 5-15 percent for anchovies, blennies, gobies, and California halibut. For these species, improving the precision of the impingement loss rate could lead to a dramatic reduction in CV.

Results are also useful for agencies seeking to identify research that will help improve understanding of the ecological significance of impingement and entrainment. Results of the sensitivity analysis and factor prioritization can help prioritize future data collection to reduce uncertainty about parameter values that have the greatest influence on uncertainty in the results of the demographic models evaluated.

## GLOSSARY

AEL	Adult Equivalent Loss
cm	Centimeter
CWA	Clean Water Act
CV	Coefficient of variation
ELS	Early life stages (typically eggs and larval stages)
EPA	U.S. Environmental Protection Agency
FH	Fecundity Hindcasting
FY	Forgone Yield
km	Kilometer
m	Meter
mm	Millimeter
MW	Megawatt
PIER	Public Interest Energy Research
RD&D	Research, development, and demonstration
SD	Standard deviation
316(b)	Section 316(b) of the Clean Water Act, concerning regulation of impingement and entrainments
YPR	Yield per recruit

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**APPENDIX A:  
Comprehensive Information About Species  
Composition and Data Sources**

**Table A.1: Species lost to impingement and entrainment in California and indication of species included in the species groups used for sensitivity analyses**

<b>Species groups</b>	<b>Species</b>
Anchovies	Northern anchovy, deepbody anchovy, slough anchovy
Gobies	Arrow goby, bay goby, black eyed goby, blind goby, chameleon goby, cheekspot goby, longjaw mudsucker, shadow goby, yellowfin goby, other unidentified gobies
Crabs	Brown rock crab, Dungeness crab, lined shore crab, mud crab, stone crab, Pacific sand crab, porcelain crab, red crab, yellow shore crab, pea crabs, pebble crab, red rock crab, Anthony's rock crab, common rock crab, hairy crab, kelp crab, lumpy crab, masking crab, brachyuran true crab, cryptic kelp crab, black-clawed crab, elbow crab, European green crab, graceful kelp crab, family Portunidae, Hempils crab, hermit crab, kelp crab, lumpy masking mole moss, Pachygrapsus sp., pugettia crab, purple shore crab, red crab, sharp nosed crab, shore crab, slender crab, southern kelp crab, spider crab, striped shore crab, swimming crab, Talipus sp., thickclaw porcelain crab, Xantus sp., yellow crab, yellow rock crab, yellow shore crab
Blennies	Bay blenny, combtooth blenny, rockpool blenny, tube blenny, mussel blenny, orangethroat blenny, other unidentified blenny species
California halibut	California halibut
Rockfishes	Aurora rockfish, black and yellow rockfish, gopher rockfish, black rockfish, blue rockfish, bocaccio, brown rockfish, calico rockfish, chilipepper, copper rockfish, flag rockfish, gopher rockfish, grass rockfish, kelp rockfish, olive rockfish, shortbelly rockfish, treefish, vermilion rockfish, yellowtail rockfish, other Sebastes species
Sufperches	Barred surfperch, black surfperch, calico surfperch, dwarf surfperch, island surfperch, kelp surfperch, pile surfperch, rainbow surfperch, rubberlip surfperch, shiner surfperch, silver surfperch, striped surfperch, walleye surfperch, white surfperch, other unidentified surfperch
Not Evaluated	Alaskan bay shrimp, american shad, anemone shrimp, angel shark, Artedius sp., barcheck pipefish, barracuda, barred sand bass, basketweave cusk eel, bat ray, bay pipefish, bay shrimp, big skate, bigmouth sole, bigscale goatfish, bigscale logperch, black bullhead, black croaker, black skate, black spotted shrimp, black tailed bay shrimp, blacksmith, blackspotted shrimp, blacktail bay shrimp, blacktail shrimp, blue lanternfish, blue mud shrimp, bonehead sculpin, broadfin lampfish, broadnose sevengill shark, broken back shrimp, broomtail grouper, brown irish lord, brown shrimp, brown smoothhound, buffalo sculpin, bullseye puffer, C-O sole, C-O turbot, cabezon, California barracuda, California butterfly ray, California clingfish, California corbina, California electric ray, California flying fish, California green shrimp, California grunion, California halibut fantail sole, California killifish, California lizardfish, California moray, California needlefish, California ray, California scorpionfish, California

**Table A.1: Species lost to impingement and entrainment in California and indication of species included in the species groups used for sensitivity analyses**

<b>Species groups</b>	<b>Species</b>
Not Evaluated	sheephead, California tonguefish, Californian needlefish, carid shrimp, catalina conger, catfish family, chinook salmon, chub mackerel, clingfishes, clinid kelpfish, codfishes, coho salmon, combfish, coralline sculpin, cortez angelfish, crevice kelpfish, croaker (other unidentified), curlfin sole, curlfin turbot, cyprinidae, delta smelt, diamond stingray, diamond turbot, dock shrimp, dover sole, drums (other unidentified), english sole, Atherinidae (other unidentified), fantail sole, finescale triggerfish, flatfish (other unidentified), flathead mullet, fluffy sculpin, franciscan bay shrimp, fringehead, garibaldi, ghost shrimp, giant kelpfish, giant sea bass, gray smoothhound, greenling, grunt, gunnel (other unidentified), prickleback gunnel, halfmoon, hatchet fish, herrings, high cockscomb, hippolytid shrimp, hitch, horn shark, hornyhead turbot, island kelpfish, jack mackerel, jacksmelt, kelp bass, kelp greenling, kelp gunnel, kelp pipefish, kelpfish (other unidentified), lampfish, lanternfish, lefteye flounder, leopard shark, Leptochelia dubia, lingcod, longfin lanternfish, longfin sanddab, longfin smelt, longspine combfish, manacled sculpin, market squid, medusafish, mexican lampfish, mexican scad, middling thread herring, monkeyface eel, monkeyface prickleback, monterey spanish mackerel, moray eel, mozambique tilapia, night smelt, northern clingfish, northern spearnose poacher, ocean sunfish, ocean whitefish, onepot fringehead, opaleye, opossum shrimp, oriental shrimp, osmeridae (other unidentified), Pacific angel shark, Pacific barracuda, Pacific bonito, Pacific bumper, Pacific butterfish, Pacific cornetfish, Pacific cutlassfish, Pacific electric ray, Pacific hagfish, Pacific hake, Pacific herring, Pacific lamprey, Pacific mackerel, Pacific moonfish, Pacific pompano, Pacific sand lance, Pacific sand sole, Pacific sanddab, Pacific sandlance, Pacific sardine, Pacific staghorn sculpin, painted greenling, Paralabrax spp., penaeid shrimp, penpoint gunnel, petrale sole, piked dogfish, pipefish spp, pistol shrimp, plainfin midshipman, poacher (other unidentified), popeye blacksmelt, prickleback, pricklebreast poacher, prickly sculpin, pygmy poacher, queenfish, ratfish, red brotula, reef finspot, ribbon prickleback, ribbonfish, righteye flounder, rock prickleback, rock sole, rock wrasse, rockweed gunnel, ronquil, rosy sculpin, roughcheek sculpin, roughneck sculpin, round herring, round stingray, Sacramento splittail, saddleback gunnel, salema, sand sole, sanddab, sarcastic fringehead, sargo, scarlet kelpfish, sculpin (other unidentified), sculpin (Artedius spp.), sculpin (Clinocottus spp.), sculpin (Icelinus spp.), sculpin (Oligocottus spp.), sculpin (Ruscarius spp.), sea porcupine, seniorita, sevengill shark, sharksucker, shovelnose guitarfish, shrimp (other unidentified), shrimp (Pandalus spp.), sidestriped shrimp, silverside, skeleton shrimp, slender sole, slimy snailfish, smalleye squaretail, smelt (other unidentified), smooth bay shrimp, smoothhead sculpin, smoothhound (other unidentified), snailfishes, snubnose pipefish, snubnose sculpin, soupfin shark, southern poacher, southern spearnose poacher, speckled sanddab, specklefin midshipman, spiny dogfish, spot shrimp, spotfin croaker, spotted bass, spotted bay shrimp, spotted cusk eel, spotted kelpfish, spotted ratfish,

**Table A.1: Species lost to impingement and entrainment in California and indication of species included in the species groups used for sensitivity analyses**

<b>Species groups</b>	<b>Species</b>
Not Evaluated	spotted sand bass, spotted scorpionfish, spotted scorpionfish, spotted turbot, squid (unidentified), staghorn sculpin, starry flounder, steelhead, stout bodied shrimp, striped bass, striped kelpfish, striped mullet, striped shrimp, sunfish family, surf smelt, swell shark, thornback, thornback, thornback ray, threadfin shad, threespine stickleback, tidepool sculpin, tidepool shrimp, topsmelt, true shrimp, tubesnout, twistclaw pistol shrimp, white catfish, white croaker, white seabass, woolly sculpin, yellow snake-eel, yellowfin croaker, zebraperch, other unidentified fish species, mysids and other unidentified invertebrates

**Table A.2: Sources of database information**

<b>Species or species group</b>	<b>Data type</b>	<b>Citation</b>
Northern anchovy ( <i>Engraulis mordax</i> )	S	Bayliff 1967, as cited in MacCall 1974
	S, F	Butler et al. 1993, as cited in Tenera Environmental Services 2000a, 2007
	S, F, M	Butler et al. 1993
	S, F	Ecological Analysts 1980
	S	Froese and Pauly 2007
	S	Hanan 1981
	S	Hewitt and Methot 1982
	S, F	Kucas 1986
	S, M	Lasker and Smith 1977
	S	MacCall 1974
	S, F	Methot 1989
	S	Lo et al. 1995
	S	Owen et al. 1989
	S	PFMC 1998
	S	Schaefer 1967, as cited in MacCall 1974
	S	Virginia Tech 1998
	F	Frey 1971, as cited in Ecological Analysts 1980
	F	MacGregor 1968, as cited in Ecological Analysts 1980
	F	Brothers 1975
	F	Baxter 1967, as cited in Wang 1986
X	U.S. EPA 2006	
Combtooth Blennies (Genus <i>Hypsoblennius</i> )	S	Love 1996, as cited in Tenera Environmental Services 2001
	S	Stephens et al. 1970, as cited in Tenera Environmental Services 2000b
	F	Tenera Environmental Services 2000b
	F	Tenera Environmental Services 2001
	X	U.S. EPA 2004
Crabs (Genus <i>Cancer</i> )	S	Wainwright et al. 1992, as cited in Armstrong et al. 2003
	S	Botsford and Hobbs 1995
	S	Carroll 1982
	S	Fernandez et al. 1993
	S	Hankin 1985
	S, F	Hankin et al. 1989
	S, F	Leet et al. 2001
	S, M	Moloney et al. 1994
	S	Orcutt et al. 1975
	S	Wickham 1979, as cited in Pauley et al. 1989
	M	Reilly 1983
	S	Shields and Kuris 1988
	S	Smith and Jamieson 1989
S	Jow 1965, as cited in Smith and Jamieson 1989	

**Table A.2: Sources of database information**

<b>Species or species group</b>	<b>Data type</b>	<b>Citation</b>
	S	Gotshall 1978, as cited in Smith and Jamieson 1989
	S	Methot and Botsford 1982, as cited in Smith and Jamieson 1989
Crabs (Genus <i>Cancer</i> )	S, M	Tenera Environmental Services 2000b
	S, F, M	Tenera Environmental Services 2001
	S	Zhang et al. 2004
	X	U.S. EPA 2006
Gobies (Family <i>Gobiidae</i> )	S, F, M	Tenera Environmental Services 2000b
	S, F, M	Tenera Environmental Services 2001
	S,F	Brothers 1975
	F	Behrents 1983, as cited in Burton et al. 2000
	F	Waples and Rosenblatt 1987, as cited in Burton et al. 2000
	F	Love 1996, as cited in Burton et al. 2000
	F	Barlow 1963, as cited in Burton et al. 2000
	F	Fitch and Lavenberg 1975, as cited in Burton et al. 2000
	F	CDFG 1982, as cited in Burton et al. 2000
	X	U.S. EPA 2006
California halibut ( <i>Paralichthys californicus</i> )	S	Emmett et al. 1991, as cited in Burton et al. 2000
	S	Gadomski and Caddell 1991, as cited in Burton et al. 2000
	S	Helvey and Witzig 1990
	S	Hobbs et al. 1992
	S	Kramer 1991
	S	MacNair et al. 2001
	S	Pauly 1979, as cited in Reed and MacCall 1988
	S	Hoening 1983, as cited in Reed and MacCall 1988
	M	Rosales-Casian 2004
	F	Caddell et al. 1990
	X	U.S. EPA 2006
Rockfishes (Genus <i>Sebastes</i> )	S	Archibald et al. 1981
	F	Adams 1992a, as cited in Burton et al. 2000
	F	Adams 1992b, as cited in Burton et al. 2000
	F	Casillas et al. 1998, as cited in Burton et al. 2000
	F	DeLacy et al. 1964, as cited in Burton et al. 2000
	F	Gunderson et al. 1980, as cited in Burton et al. 2000
	F	Haldorson and Love 1991, as cited in Burton et al. 2000
	F	Hart 1973, as cited in Burton et al. 2000
	F	Love and Johnson 1998, as cited in Burton et al. 2000
	F	Love and Westphal 1981, as cited in Burton et al. 2000
	F	Love et al. 1990, as cited in Burton et al. 2000
	F	Love 1978, as cited in Burton et al. 2000
	F	Love 1996, as cited in Burton et al. 2000
	F	MacGregor 1970, as cited in Burton et al. 2000
	F	Matarese et al. 1989, as cited in Burton et al. 2000

**Table A.2: Sources of database information**

<b>Species or species group</b>	<b>Data type</b>	<b>Citation</b>
	F	Miller and Giebel 1973, as cited in Burton et al. 2000
	F	Miller and Giebel 1973, as cited in Russell and Hanson 1990
Rockfishes (Genus <i>Sebastes</i> )	F	Miller et al. 1967, as cited in Burton et al. 2000
	F	Phillips 1964, as cited in Burton et al. 2000
	F	Romero 1988, as cited in Burton et al. 2000
	F	Wakefield and Smith 1990, as cited in Burton et al. 2000
	F	Wales 1953, as cited in Burton et al. 2000
	F	Methot et al. 2003, as cited in Gilbert 2006
	F	MacGregor 1970, as cited in Gilbert 2006
	F	Boehlert et al. 1982, as cited in Gilbert 2006
	S	Washington et al. 1978, as cited in Burton et al. 2000
	S	Barker 1979, as cited in Burton et al. 2000
	S	Yamanaka and Kronlund 1997, as cited in Burton et al. 2000
	S	McClure 1982, as cited in Burton et al. 2000
	S	Six and Horton 1977, as cited in Burton et al. 2000
	S	Six 1976, as cited in Burton et al. 2000
	S	STAR 1999, as cited in Burton et al. 2000
	S	Wallace et al. 1999, as cited in Burton et al. 2000
	S	Rosenthal et al. 1982, as cited in Burton et al. 2000
	S	Dorn 2000, as cited in Burton et al. 2000
	S	Wallace and Tagart 1994, as cited in Burton et al. 2000
	S, F	Tenera Environmental Services 2000a, as cited in Burton et al. 2000
	S	Adams and Howard 1996, as cited in Burton et al. 2000
	S	Gotshall 1969, as cited in Burton et al. 2000
	S	Archibald et al. 1981, as cited in Burton et al. 2000
	S	Wilson and Boehlert 1990, as cited in Burton et al. 2000
	S, F	STAT 1999, as cited in Burton et al. 2000
	S	Butler et al. 1995, as cited in Burton et al. 2000
	S	Ianelli et al. 1994, as cited in Burton et al. 2000
	S	Miller 1985, as cited in Burton et al. 2000
	F, M	Berkeley et al. 2004
	M	Burton et al. 2000
	S	Calvanese 2006
	S	Clark 2002
	S	Clausen and Heifetz 2000
	M	Collins 2004
	S	Fargo 2002
	S	Fraidenburg 1981
	S	Gunderson 1977, as cited in Fraidenburg 1981
	S	Gunderson et al. 2003
	M	Hoenig 1983

**Table A.2: Sources of database information**

<b>Species or species group</b>	<b>Data type</b>	<b>Citation</b>
	M	Karpov et al. 1995
	S	Leaman and Nagtegaal 1987
Rockfishes (Genus <i>Sebastes</i> )	F, M	Leet et al. 2001
	S	Malecha et al. 2007
	S	Meyer 1992
	S	O'Connell et al. 2005
	M	O'Farrell and Botsford 2006
	S	Hoening 1983, as cited in O'Farrell and Botsford 2006
	S	Love et al. 2002, as cited in O'Farrell and Botsford 2006
	S	Wyllie Echeverria 1987, as cited in O'Farrell and Botsford 2006
	S	Love and Westphal 1981, as cited in O'Farrell and Botsford 2006
	S, M	Pearson and Gunderson 2003
	S	Pearson et al. 1991
	S	Leaman 1986, as cited in Pearson et al. 1991
	S	Lenarz 1984, as cited in Pearson et al. 1991
	F, M	Phillips 1964
	F	Phillips 1964
	S	Ralston et al. 2003
	S	Russell and Hanson 1990
	S	Gotshall 1987, as cited in Russell and Hanson 1990
	S	Lenarz 1987, as cited in Russell and Hanson 1990
	S	Leaman and Nagtegall 1987, as cited in Russell and Hanson 1990
	S	Tagart 1989, as cited in Russell and Hanson 1990
	S	Archibald et al. 1981, as cited in Russell and Hanson 1990
	S	Spencer and Ianelli 2006
	S	Stanley et al. 2005
	S	Stanley 1999, as cited in Stanley et al. 2005
	M	Stein and Hassler 1989
	F	DeLacy et al. 1964, as cited in Stein and Hassler 1989
	S, M	Tenera Environmental Services 2000a
	S, F, M	Tenera Environmental Services 2001
	S	Yoklavich et al. 1996
	S	Yoklavich 1998
	S	Archibald et al. 1981, as cited in Malecha et al. 2007
	S	Chilton and Beamish 1982, as cited in Malecha et al. 2007
	S	Heifetz and Clausen 1991, as cited in Malecha et al. 2007
	S	Nelson and Quinn 1987, as cited in Malecha et al. 2007
	S	McDermott 1994, as cited in Malecha et al. 2007
	S	Wallace 2001, as cited in O'Connell et al. 2005
	S	Yoklavich et al. 1996, as cited in Yoklavich 1998
	S	Ralston et al. 1996, as cited in Yoklavich 1998

**Table A.2: Sources of database information**

Species or species group	Data type	Citation
	X	U.S. EPA 2006
Surfperches (Family <i>Embiotocidae</i> )	S, F, M	Burton et al. 2000
	F	CDFG 2007b
	F	Carlisle et al. 1960
	S	Eckmayer 1975, as cited in Lane 2002
	F, M	Fritzsche and Collier 2001
	F	Ryan et al. 2004
	F	Swedberg 1965, as cited in Lane et al. 2002
	F	Gnose 1967, as cited in Lane et al. 2002
	F	Wilson and Millemann 1969, as cited in Lane et al. 2002
	F	Miller and Lea 1972, as cited in Lane et al. 2002
	F	Bennett and Wydoski 1977, as cited in Lane et al. 2002
	F	Baltz 1984, as cited in Lane et al. 2002
	F	Leet et al. 1992, as cited in Burton et al. 2000
	F	Miller 1960, as cited in Burton et al. 2000
	F	Fritzsche and Hassler 1989, as cited in Burton et al. 2000
	F	Breder and Rosen 1966, as cited in Burton et al. 2000
	F	Triplett 1960, as cited in Burton et al. 2000
	F	Baltz 1984, as cited in Burton et al. 2000
	F	Gordon 1965, as cited in Burton et al. 2000
	F	Behrens 1977, as cited in Burton et al. 2000
	F	Gnose 1967, as cited in Burton et al. 2000
	F	Love 1996, as cited in Burton et al. 2000
	F	DeMartini et al. 1983, as cited in Burton et al. 2000
	F	Garrison and Miller 1982, as cited in Burton et al. 2000
	F	DeLeon 1999, as cited in Burton et al. 2000
	F	Odenweller 1971, as cited in Burton et al. 2000
	F	Odenweller 1975, as cited in Burton et al. 2000
F	Eigenmann 1892, as cited in Burton et al. 2000	
F	Bennet and Wydoski 1977, as cited in Burton et al. 2000	
F	Banerjee 1971, as cited in Burton et al. 2000	
F	Wares 1971, as cited in Burton et al. 2000	
M	Swedberg 1965	
X	U.S. EPA 2006	

Key:

S: Survival.

F: Fecundity.

M: Miscellaneous information.

X: Size.